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MAY 82 J BACKOVSKY, S B MARTIN, R MCKEE EMW-C-0559

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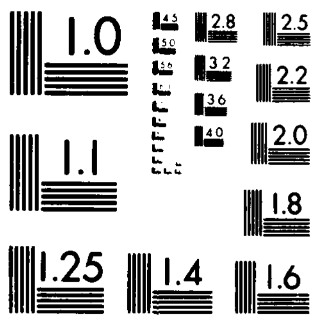

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May 1982

Final Report

Prepared for:

FEDERAL EMERGENCY MANAGEMENT AGENCY
Washington, D.C. 20472

Contract No. EMW-C-0559
FEMA Work Unit 2564A

SRI Project PYU 3341

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By: Jana Backovsky
Stanley Martin
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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER	2. GOVT ACCESSION NO. AD-A117625	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) EXPERIMENTAL EXTINGUISHMENT OF FIRE BY BLAST		5. TYPE OF REPORT & PERIOD COVERED Final Report
		6. PERFORMING ORG. REPORT NUMBER PYU 3341
7. AUTHOR(s) Jana Backovsky, Stanley B. Martin, Robert McKee		8. CONTRACT OR GRANT NUMBER(s) EMW-C-0559
9. PERFORMING ORGANIZATION NAME AND ADDRESS SRI International, 333 Ravenswood Avenue, Menlo Park, CA 94025		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 2564 A
11. CONTROLLING OFFICE NAME AND ADDRESS Federal Emergency Management Agency, Washington, D.C. 20472		12. REPORT DATE May 1982
		13. NUMBER OF PAGES 97
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Federal Emergency Management Agency, Washington, D.C. 20472		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release, Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Blast/fire interactions
Shocktube facility
Flame displacement
Fire extinction by airblast
MILL RACE event
Debris fires blowout
Airblast simulation
Thermal radiation source
Wood cribs
Class-B fuels

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Experiments on extinction of fires by airblast were continued in the shocktube facility dedicated to blast/fire interactions studies, and the facility was further improved toward a full, thermal/blast simulation capability, which will include a thermal radiation source.

The experimental efforts were aimed toward improving our understanding of the physical mechanisms and scaling rules of blast extinguishment of fires through (1)tests with various common liquid (class B) fuels of different

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20. Abstract (concluded)

physicochemical properties and burning behavior and (2) tests with wood cribs of various element (stick) thicknesses and consequently varying burning behavior and time scales. Limited shocktube tests were also conducted in preparation for the MILL RACE event featuring blast extinction of fires on cellulosic debris.

The significance of fuel type in ease of extinction by short positive-phase-duration airblast was confirmed. Most notable is that many class B fuels may have a significantly lower extinction-threshold overpressures, even with the short-duration airblasts used, than past tests with hexane had indicated. All tests indicated that flame flashback to the fuel bed from the downstream turbulent wake was the flame-retaining mechanism in nonextinction cases.

The tests demonstrate that displacement of flame off the fuel bed may be necessary but not always sufficient for extinguishing flaming combustion. For short-duration airblasts, turbulence and recirculation-producing wakes and obstacles are instrumental in producing actual extinction thresholds in class B fuels that are above the low (less than 1 psi) airblast levels required for simple flame displacement. Consequences for class B fuels of longer duration airblast accompanied by large particle and flame displacement require further study.

Shocktube tests with wood crib (class A) fires further demonstrated the role in blast/fire interaction of active-char combustion and heat retention for cellulosic, charring materials, as well as the role of the crib matrix in reducing the heat losses of the internal elements and in perturbing the airblast. A limiting state is reached in the crib fire development that renders the burning crib unextinguishable by short duration, up to 10 psi overpressure airblasts. Such a limiting state is simply, but not exclusively, described by the time delay between freeburning crib fire initiation and blast arrival (preburn time) or, alternatively, by the crib weight loss due to freeburning before blast arrival.

Comparison of the observed limiting preburn times--limits of extinguishability by airblast--suggests a 40% reduction in time scale from the 3/4-in. to the 3/8-in. stick cribs, which is slightly in excess of the reduction theoretically predicted by a square-root-of-fuel-thickness scaling rule. Below the limiting preburn time, the extinction overpressure threshold increases with preburn time. Both crib types become unextinguishable when comparable percentage weight loss has been reached, and extinction thresholds in terms of percent crib weight loss at airblast arrival are quite similar. The square-root-of thickness scaling rule warrants further development and generalization to fully correlate the fuel form, fuel type, preburn time and extinction overpressures for class A fuels.

SUMMARY

Objective and Scope

The overall objective of this experimental program is to determine and evaluate the physical variables that govern airblast extinction of sustained burning, in representative fuels, using a specially designed shocktube facility to simulate pressure pulses that are characteristic of nuclear explosions in air. The experiments are also selected to provide both an empirical base for analytical models being developed concurrently elsewhere and data for direct validation in high-explosive field tests such as MILL RACE. This year's efforts were aimed toward (1) establishing experimentally the scaling rules of blast extinguishment of fires for various fuels and geometries, (2) installing and testing a thermal radiation source (accessory to the shocktube at Camp Parks), and (3) employing the thermal source in full simulation (thermal/blast) shocktube tests duplicating MILL RACE conditions in preparation for and validation of the blast/fire field experiments.

Approach

Because the components of the thermal source that we expected to use and its design specifications were not delivered in full by another FEMA contractor during the term of the present SRI project, our experiments were performed by substituting low-power thermal fire-initiation sources.

On the basis of results and understanding obtained from previous (1980) shocktube tests, we used wood cribs of two different element thicknesses to investigate the scaling of preblast burning time and the role of fuel-element thickness in heat-retentive, charring fuels. Crib dimensions were the same as in the 1980 study, but the fuel elements (sticks) making up the crib were scaled down by a factor of 2 in thickness (to 3/8-in.) and thus reduced by a factor 4 the fuel-element cross-sectional area. Theory predicts a 41% increase (i.e., $\sqrt{2}$) in specific burning rate

(weight loss per unit fuel surface area) during steady burning, and shortened fire-time scale to 70% of the characteristic times for the thicker element crib; a 43.5% increase in specific burning rate was observed in verification tests.

The dependence of blast/fire effects on scale (fire size) was established for hexane in a previous SRI study. Of interest this year has been the role played by fuel type--notably, the pertinent physico-chemical properties--compared with the previously observed significant role played by wakes and eddies in the airblast flowfield. The fuels (kerosene, n-pentane, and acetone) were chosen to emphasize this variability in fuel properties when tested as 3-fot-long pool fires for extinction by unobstructed, zero-angle-of-incidence airblast waves.

Significant Results

The shortening of the preburn times (preselected delays between ignition and shock firing) at which the crib fires resist permanent extinction by airblasts of given overpressures was well confirmed by experiments with the new cribs. Comparison of the limiting preburn times--limits of extinguishability by airblast--suggests a 40% reduction in time scale from the 3/4-in. to the 3/8-in. stick cribs. Below the limiting preburn time the extinction overpressure threshold increases with preburn time. Both crib types become unextinguishable when comparable percentage weight loss has been reached (23.5% and 28% for the 3/4 and 3/8-in. stick cribs, respectively) and correlations of extinction thresholds in terms of percent crib weight loss at airblast arrival are quite similar.

Shocktube experiments with Class B fuels provided some surprising new information. The surprising aspect of these tests was the relatively low extinction blast-overpressure thresholds observed for the fuels tested: kerosene (1.5-2.0 psi mean overpressure); n-pentane (2.8-3.0 psi); acetone (1.5-1.9 psi). These thresholds are between the values for n-hexane (5.1 psi) and methanol (less than 1 psi) obtained previously. Except for hexane, the thresholds correlate with the effective fuel volatility (heat required to gasify the fuel).

High-speed photographic records suggest the mechanism by which volatile fuels resist blast extinction in the shocktube tests, placing the flame displacement concept into better perspective. In a typical class B fuel shocktube experiment, the arriving shock displaces the flame off the fuel bed cleanly and seeps it downstream at near the particle velocity of the airblast. The displaced flame survives downstream of the test section for up to 150 ms--or the full extent of the positive phase duration in short-duration tests. The displaced flame essentially becomes a wake flame and is fueled by vapors swept from the still-volatilizing fuel bed.

The intense, turbulent mixing of the fuel-vapor/air mixture and the hot combustion gases in the shear mixing layer downstream of the fuel bed and of the test stand (rather than flow recirculating, as in the case with flow obstacles) substantially increases the fuel burning velocity. When the particle velocity drops near the end of the positive phase, the high burning velocity provides for flashback upstream to the fuel bed and for eventual reestablishment of flame on the fuel bed. Fuel volatility plays a part in the amount of fuel vapor supplied to the wake: if the fuel volatility is low, the mixture in the wake is lean and the burning velocity drops too low for combustion to persist until flow particle velocity decreases sufficiently for flashback.

Recommendations

A systematic investigation of the two principal airblast variables (positive phase duration and delay in airblast arrival) associated with variations in conditions of nuclear explosions--and already shown to have a strong influence on airblast extinction of fire--remains a high priority activity of the FEMA-funded study of blast/fire interactions.

Beyond the immediate requirements for data directly applicable to forecasting fire effects of nuclear explosions in a few representative classes of practical urban materials, the longer term goal (of interest to both FEMA and DNA) is a reliable and generally applicable methodology for damage/threat prediction. Complications due to geometry will need experimental investigation, scaling rules will need to be developed and verified. Some progress has already been achieved and is reported here.

Previous limited experiments in the blast/fire facility showed strong and complicated effects of nonflat and other airflow-perturbing geometries on fire behavior. Present tests on common liquid fuels representing various combinations of physico-chemical properties demonstrate the strong and as yet unpredictable effects of fuel type. These observations point to the limited practical applicability of a simple flame-displacement mechanism as a basis for theoretical development. These results affirm the need for a fundamental understanding of the fluid dynamics of compressible/transient fluid flow interactions with diffusional/unsteady combustion processes.

Results of last year's experiments with wood cribs ignited with alcohol had already shown that the strength of the airblast needed to blow flames out depends strongly on the preburn time. Present tests on cribs made up of thinner elements confirm the role of preburn time, and the results are instrumental in developing and testing scaling rules for preburn time. The application of such scaling rules to even finer materials--which are more readily ignited by the nuclear thermal pulse—requires further verification.

CONTENTS

FIGURES

TABLES

ADMINISTRATIVE INFORMATION

This is the final report of work accomplished for the Federal Emergency Management Agency (FEMA) under Contract No. EMW-C-0559; it reports the third year of work under FEMA Work Unit 2564A. With the publication and distribution of this report, all contractual requirements of the subject contract are satisfied.

A detailed approach was documented in the approved Work Plan (reproduced as Appendix A). The objectives inherent in the Statement of Work and the Work Plan were as follows:

(1) To further enhance the simulation versatility of the blast/fire shocktube facility by addition of a thermal radiation pulse capability for ignition of (especially class A) fuel complexes. This will permit highly realistic simulation of primary fire-starting and allow the delay between ignition and shock arrival to be included as a test variable.

(2) To employ this thermal pulse capability in concert with the shocktube to duplicate MILL RACE conditions, thereby providing data for direct validation in the MILL RACE event in the fall of this year (1981).

(3) To further investigate the mechanics of fire extinction by airblast to develop the empirical base for data correlation and to test theoretically derived scaling principles.

Objectives (2) and (3) have been fulfilled to the extent possible without the availability of the thermal radiation source. Objective (1) has not as yet been fulfilled for the reasons given below.

Full delivery of hardware and design guidance by SAI has not been made as of this writing. Consequently, the completion of the thermal source has been delayed, and it could not be used in the experimental phases of the current contract.

The installation at Camp Parks has proceeded as far as it can go until SAI completes delivery of its contractual obligations. The electrical power source (132 heavy-duty, truck batteries with charging

system) is assembled and housed in its weather-protected enclosure, adjacent to the Quonset hut that covers the experimental arena through which the shocktube runs. The batteries will be maintained and kept charged to minimize deterioration. At present, we do not know how much longer this facility will remain unfinished. In the meantime, maintenance costs and inflation will deplete the funds remaining to complete the installation and checkout.

I INTRODUCTION

In modern warfare, whether the bombs and warheads contain conventional or nuclear explosives--and even when the attack is directed only at military targets and industries--urban society can suffer heavy collateral damage, human injury, and loss of life. Fire was the principal destructive agent in World War II; and, despite innovations in weaponry since, fire remains a first-rank threat to life and property. Any reasonable extrapolation to thermonuclear attack on the United States today implies a fire threat of calamitous magnitude.

Unlike the immediate effects of a nuclear explosion, fire continues for some time to destroy property and threaten lives, and it may carry destruction outside the area of immediate damage if conditions favorable to fire spread exist. Nevertheless, fire is potentially amenable to control, and much of its destructiveness is, at least in principle, subject to mitigation. Only its magnitude--both its extent and intensity (i.e., power density)--makes fire control seem futile in the wake of a nuclear attack. Yet this magnitude remains quite uncertain, especially in the early stages of fire development when countermeasures are apt to be most effective.

The uncertainty is due, by and large, to unknown interactions of airblast with burning materials, including outright extinguishment. There is too little actual experience from which to draw reliable estimates. Depending on the assumptions made, analytical estimates of the fire threat can range between the relatively unimportant to the totally unmanageable. The biggest of the currently recognized contributing uncertainties is airblast extinction.

These technical deficiencies notwithstanding, analytical models intended to forecast the effects of fires resulting from nuclear explosions have a definite place in national security planning. Althought the respective applications of the two concerned federal agencies--the Federal

Emergency Management Agency and the Defense Nuclear Agency--are often quite different, the planners in both recognize a continuing research requirement in support of predictive modeling of fire damage and threat. A major goal of such research is to improve confidence in model forecasts by reducing technical uncertainties.

The research reported here is the third year of an experimental investigation of one of the principal remaining uncertainties, airblast extinction of fires. It complements, and is coordinated with, a contemporary activity funded by DNA. The primary objectives of the research reported here--experimentation on idealized representations of class A and B fuels in the specially designed airblast facility (Fig. 1), developed and operated by SRI International at Camp Parks, CA--were an empirical basis for data correlation and scaling principles. Secondary objectives of the research were to further enhance the simulation versatality of the facility, by adding a thermal radiation pulse accessory (designed by Science Applications, Inc.) and to use this enhanced capability to support a FEMA-sponsored validation experiment at the high-explosive MILL RACE event.

The two previous years of shocktube experiments are described in Refs. 1 and 2; Refs. 3 and 4 describe the Blast/Fire Facility, its capabilities and operation. Brief descriptions of past shocktube experimental results are included in this report, in the respective subject chapters.

The "bottom line" for blast/fire research sponsored by FEMA is cost/effective plans for damage mitigation in accordance with the perceived threat. The value of the research results is measured by how reliably they allow the threat to be perceived and how effective the suggested countermeasure concepts are. In particular, blast/fire research singles out the potential for property damage, injury, and death caused by fire, over and above that resulting from blast effects alone. Because we lack sufficient experience with wartime use of nuclear weapons to rely on judgment, and testing of concepts with actual nuclear explosions in the atmosphere is denied us by treaty, the only resort left is experimental simulation.

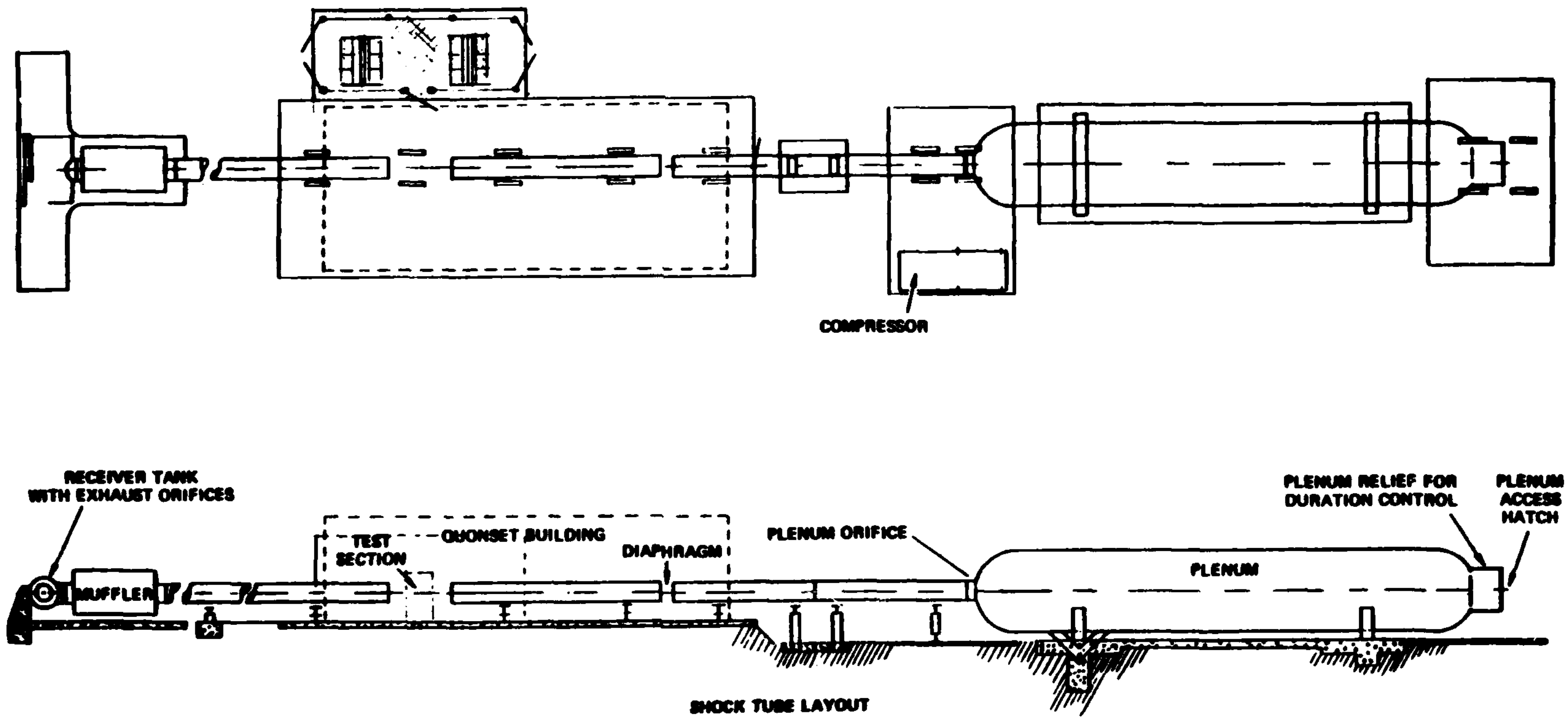

FIGURE 1 BLAST/FIRE SHOCKTUBE FACILITY

II WOOD CRIB TESTS: FUEL ELEMENT SCALING

Previous Shocktube Experiments Using Wood Cribs

The 1980 shocktube tests with cribs are described in detail in Ref. 1. In those tests, the preburn time (the time between fuel ignition and shock arrival) was a significant experimental variable. The extinction and nonextinction regions were mapped out by "fire out" and "fire not out" points in the overpressure-preburn time plane as shown in Fig. 2. The nonextinction regions bound the extinction "peninsula" at the low and high overpressures and for times greater than a limiting time. The threshold curve was thus a double-valued curve with the apex at the limiting time beyond which no extinction case was observed. The percentage of weight loss during the preburn stage (i.e., at shock arrival) was found to be an equally useful variable for correlating the same extinction data, as can be seen in Fig. 3. With the repeatable crib weight loss history, each of these curves could, in fact, be produced from the other with reasonable accuracy.

The thermal state, as well as the extent of pyrolysis, of the crib elements achieved at the limiting preburn time presumably controls the crib response and is sufficient to cause reignition after blast passage, even with complete temporary extinction of flaming combustion by flame blowoff. The relevant conditions of the limiting thermal state hypothetically are the char layer thickness and the temperature profiles in the char layer and in the virgin fuel.

Purpose of Present Tests

With the results and understanding obtained from previous (1980) shocktube tests (Ref. 1) with cribs, our purpose in the present series of shocktube experiments was to investigate the effect of the fuel element thickness on the blast extinction behavior of wood crib fires; specifically, the relationship between the fuel element thickness, the preburn time, and the threshold blast overpressures for permanent crib fire extinction.

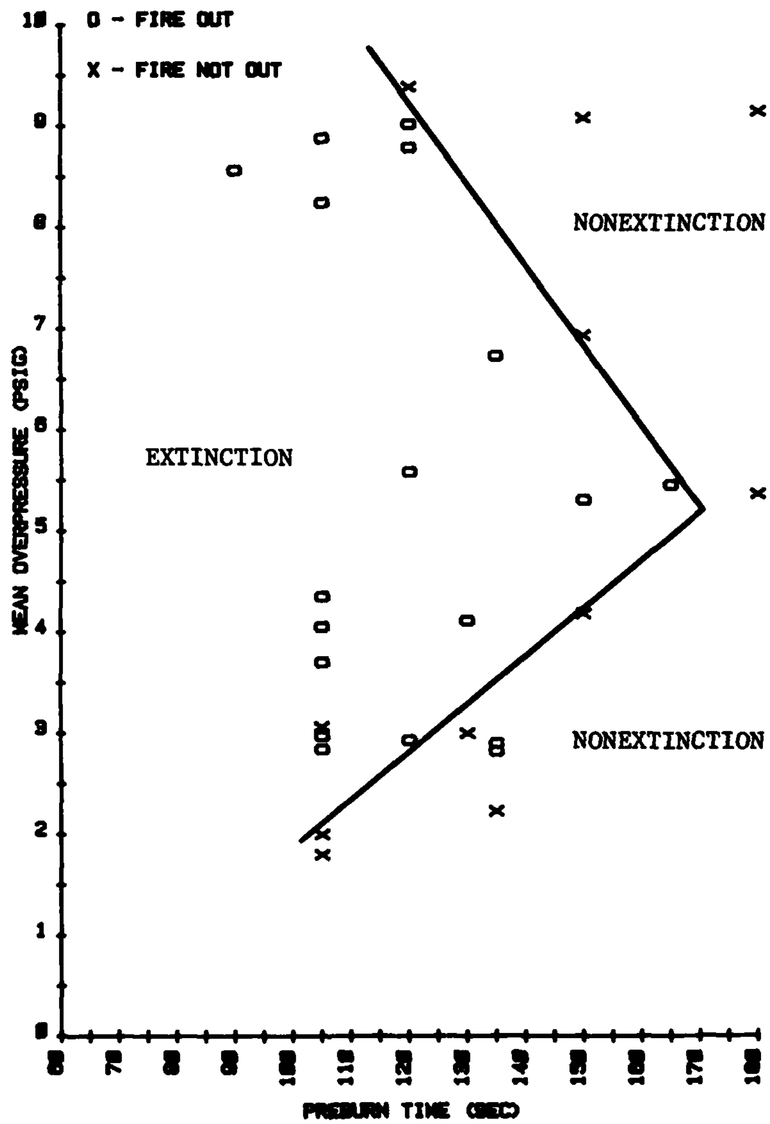

FIGURE 2 BLAST EXTINGUISHMENT OF CRIB FIRES, BASED ON PREBURN TIME; 1980 TESTS (FROM REF.1) WITH SHORT DURATION AIR-BLASTS

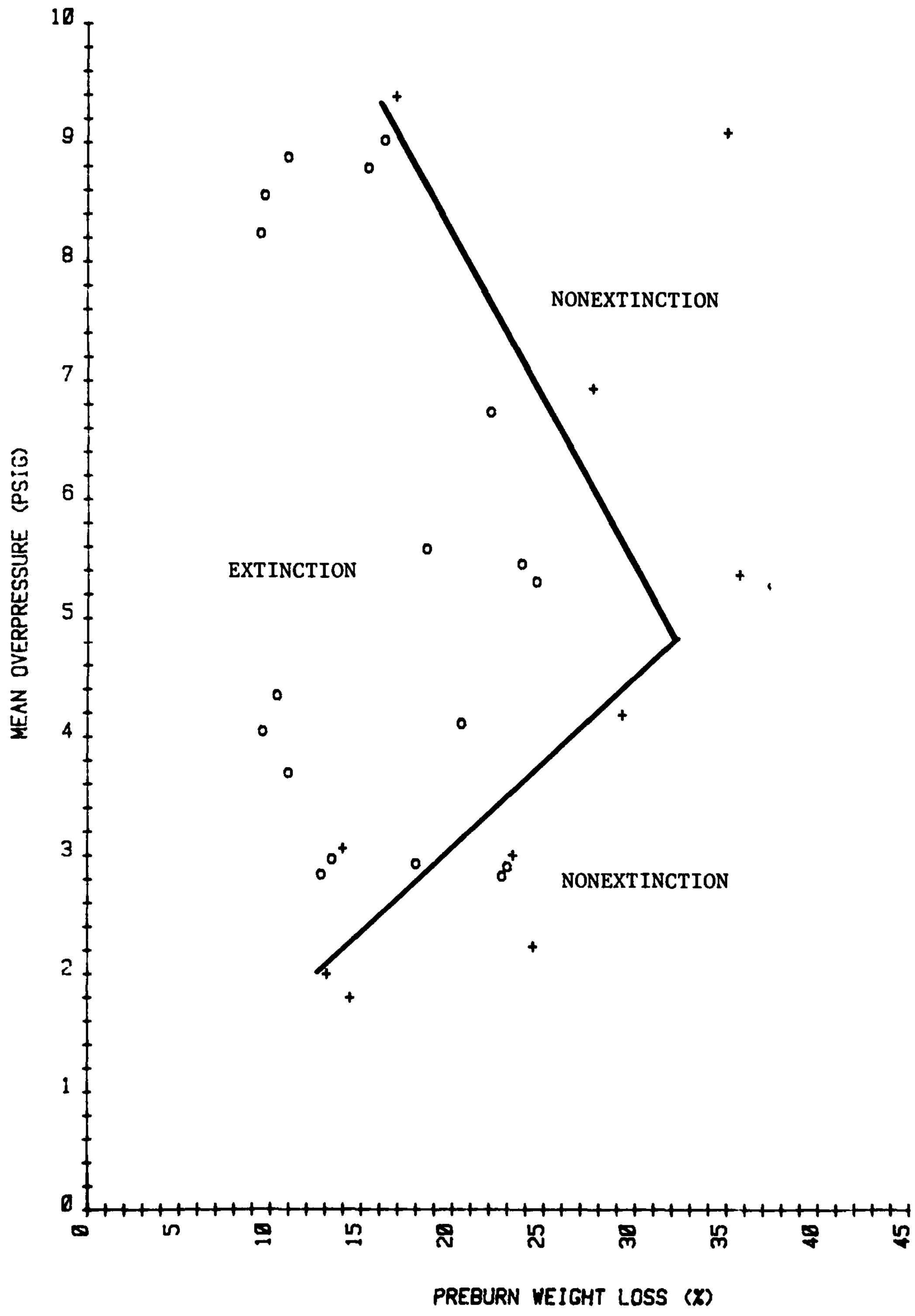

FIGURE 3 BLAST EXTINGUISHMENT OF CRIB FIRES, BASED ON PREBURN WEIGHT LOSS; 1980 TESTS (FROM REF.1) WITH SHORT DURATION AIRBLASTS

The specific questions to answer were:

- Could we predict the conditions under which a wood crib, with fuel elements of a particular thickness, is blast extinguished?
- What is the limiting preburn time (thermal state) for permanent extinction of thin materials, which may be more readily ignited by the nuclear thermal pulse?
- Or, more generally, is there a limiting thermal state (extent of burning?) from which the response of charring materials of various thicknesses could be predicted? Ultimately, it would be desirable to predict this for various fuels.

Development of Scaling Rules

The scaling parameters of interest in this report pertain primarily to the thermal state of the fuel at blast arrival. The preburn time, i.e., the time between fuel ignition and shock arrival, had been a significant experimental variable in the 1980 shocktube tests with cribs. For the cribs used in 1980 (made up of 3/4-in. square sticks), there was a limit preburn time, after which the cribs were unextinguishable with blasts of 1-10 psi overpressures. A fuel arrangement was specifically designed to provide an empirical basis for scaling the preburn duration and subjected to a range of overpressures in the shocktube. Well-developed empirical relations for crib burning guided the design. These concepts, presented below in summary, are discussed in detail in Appendix C.

What was desired was a crib design analogous as much as possible to the 3/4-in. stick cribs used in the past, but burning at a significantly higher specific rate (i.e., higher weight loss rate per unit surface area) and having, consequently, a shorter relative burning time scale. The crib should be loosely packed, which results in well-ventilated, surface-area controlled burning when steady burning is achieved (as is true for the previously used 3/4-in. stick cribs).

A well-established correlation indicates that for such loosely packed wood cribs the steady-weight loss rate $\dot{m}$ (which corresponds to the maximum weight loss rate) is proportional solely to the total surface area A_s of the crib and the inverse square root of the stick thickness b, or $\dot{m} \approx K A_s (b)^{-1/2}$, where the constant of proportionality, K, includes the

material properties (including moisture). To increase $\dot{m}/A_s$, the specific weight loss rate, the stick thickness needs to be decreased. The stick dimensions chosen were 3/8-in. square; $\dot{m}/A_s$ was expected to increase by a factor of $(2)^{\frac{1}{2}}$ or about 41.4%, verified by the 43.5% increase recorded in preparatory burning (weight loss) rate tests.

The new crib design chosen is shown in Fig. 4. The new crib is made of 3/8-in. square elements spaced 3/4-in. apart, and consists of five layers. The overall dimensions of the new crib, as well as the method of support, are close to those of the previous cribs. After the steady weight-loss-rate regime is reached, the empirical relation applies and the specific weight loss can be represented as a function of time by

$$\Delta m/A_s = K\ (b)^{-1/2}(t - t^*),$$

where t is the time elapsed from ignition (i.e., preburn time) and t^* is the intercept value on the time-coordinate on the $\Delta m/A_s$ versus t plot with the slope $\dot{m}/A_s = Kb^{-1/2}$. This linearization of the weight loss curve yields the scaled (but dimensional) quantity $K(t - t^*)/b^{1/2}$.

Crib Design and Preburn Conditions

The crib shown in Fig. 4 was assembled using trivet construction: a set of grooves is milled at right angles into both top and bottom of 3/4-in. thick pine shelving, running crosswise or lengthwise. The result is a 2-layer unit of 3/8-in. thick elements spaced 3/4-in. apart. This method of construction simplifies assembly and minimizes foreign material (glue or nails) needed to assemble the crib. The 5-layer crib used 2 trivet units, with a layer of longitudinal sticks in the middle. The crib supports were originally designed to be three 3/4-in. sticks as shown in Fig. 4, and, in fact, shocktube tests No. 39-62 used cribs with all three support sticks in place.

It became apparent that (1) the center support was not necessary for blast-reinforcing the crib and (2) more uniform, repeatable ignition would be achieved without it; therefore, all tests after No. 62 used only the two end support sticks, on upstream and downstream end of crib.

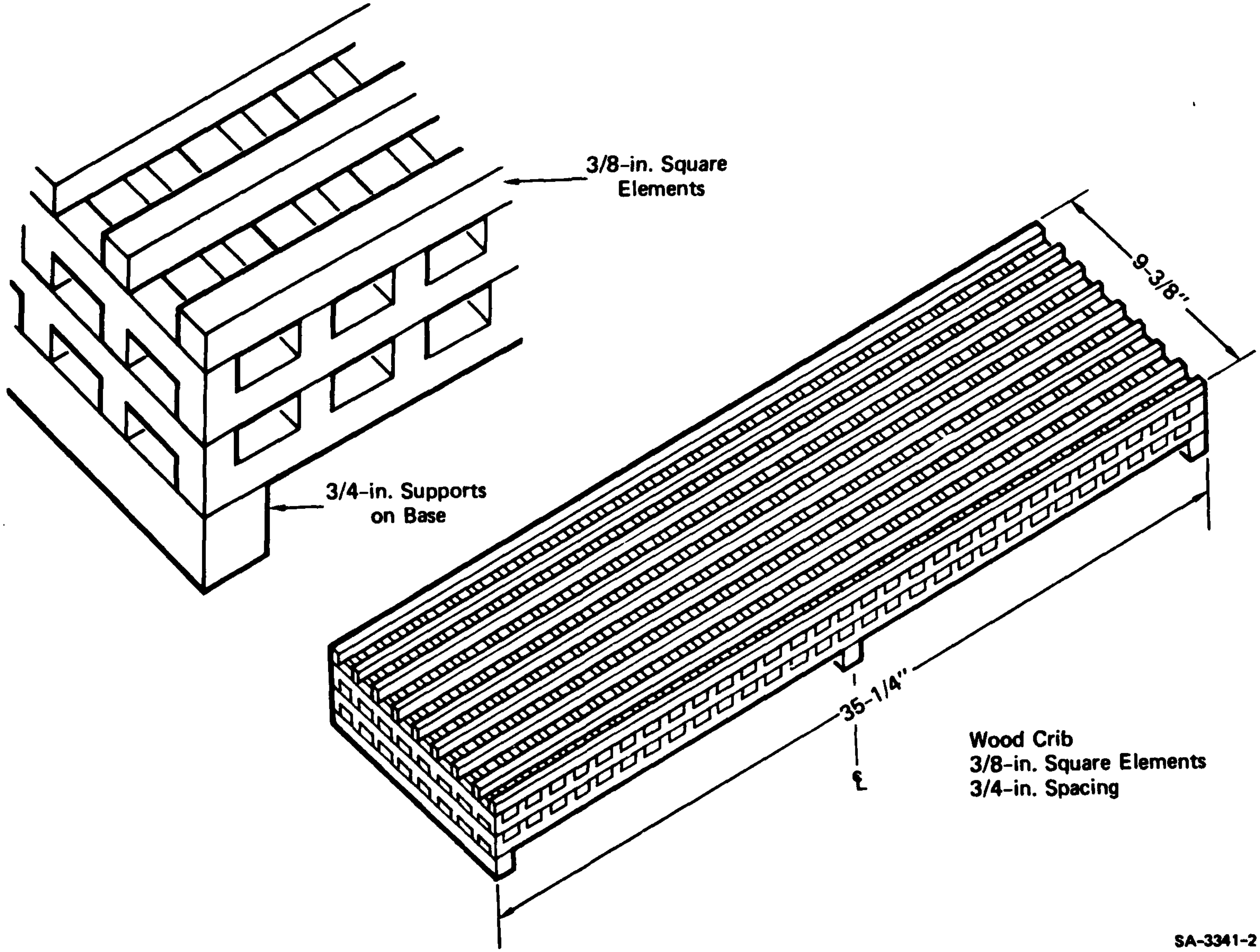

FIGURE 4 NEW CRIB DESIGN, WITH 3/8-in. ELEMENTS

The placement of the crib was analogous to that used for the 3/4-in. cribs, shown in Fig. 5. The crib was fastened to the test stand by four triangular steel brackets along the four vertical edges. The amount of crib surface covered by the brackets was negligible and the need for vertical rod fasteners (used in 1980 tests) was eliminated.

The crib size (number of layers and dimensions) and the crib supports were chosen to make the cribs aerodynamically similar to the previously used cribs. The 3/4-in. supports, giving a 3/4-in. clearance between the crib and the test stand, allowed for comparable air entrainment through the crib bottom, and allowed for similar ample ventilation of the crib interior where the most important part of combustion--on and between the crib interior surfaces--occurs. Because there was the same spacing between elements (3/4-in.), the cross sectional area of each vertical vent (shaft) in the crib remains the same, although there are now slightly more vents.

The preburn conditions were altered only in the time scale. The 3/4-in. stick cribs had an ignition period of 60 s and the total preburn times (from ignition of accelerant to shock arrival) ranged from 90 to 180 s. Due to the accelerated burning in the 3/8-in. stick cribs, discussed in the preceding section, the ignition period was shortened to 30 s and the total preburn times used shifted down to the range of 60 to 120 s. The ignitor fluid used was again propyl alcohol. For those cribs that used only the two edge support sticks (the center stick removed), the wick now uniformly covered the area underneath the crib.

Extinction Thresholds: Data Interpretation

The test data for the 3/8-in. stick cribs are summarized in Table B-2 (Appendix B). All 34 tests used short positive phase duration pressure pulses which are produced by pressurization of the 30-ft tube section at the upstream end. Figure 6 shows typical short duration pressure pulses used during the year's testing; an almost ideal flat-topped profile is obtained. The flat-topped profile is not intended to duplicate the classical pulse shape of nuclear explosions--which would be obtained by use of the main pressure plenum--but serves as a useful research tool enabling study

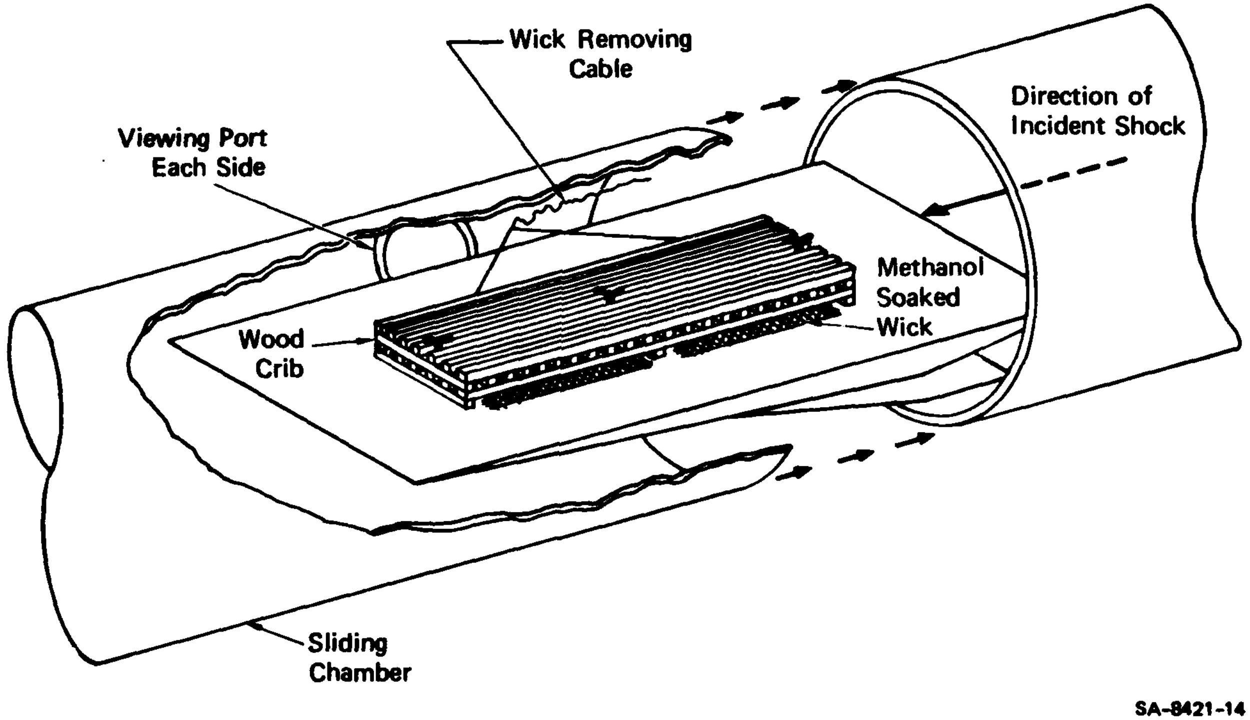

FIGURE 5 SHOCKTUBE TEST SECTION WITH CRIB, BEFORE IGNITION

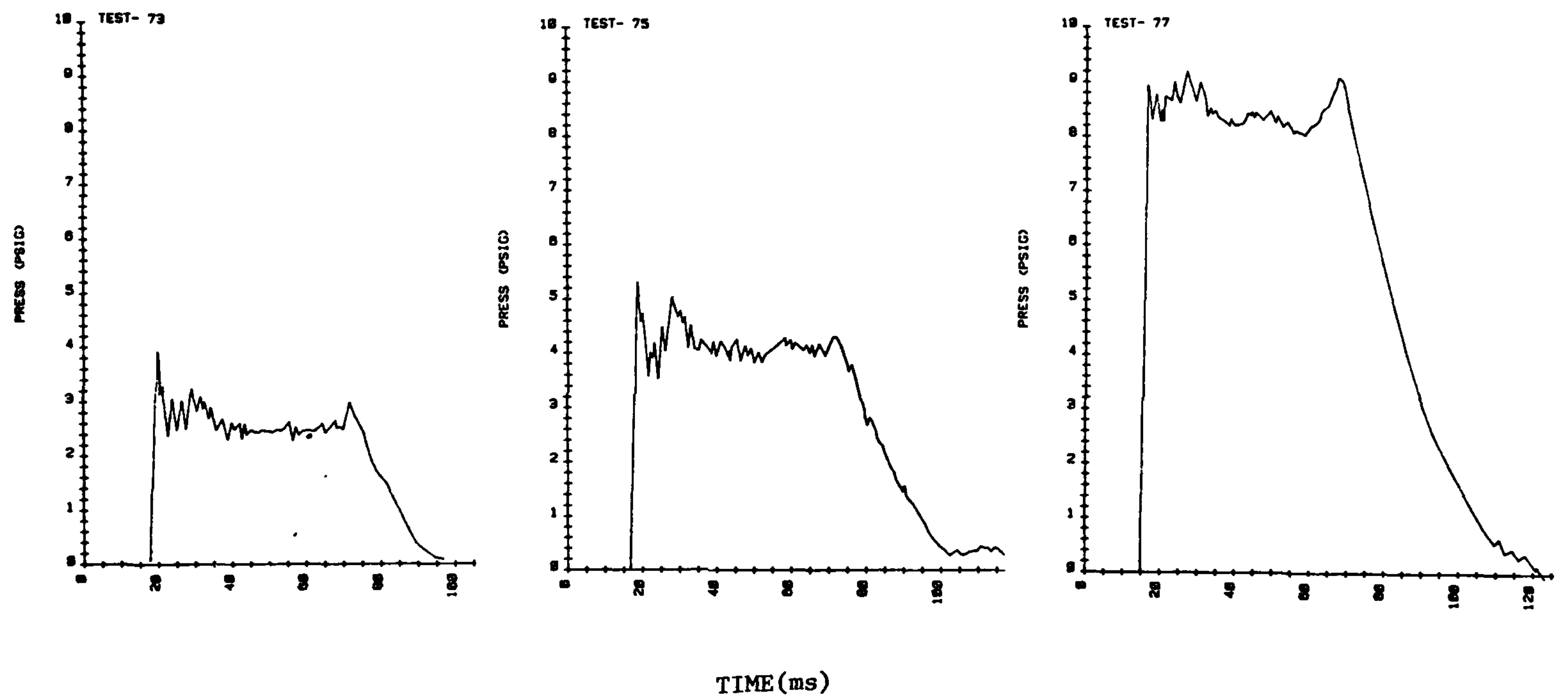

FIGURE 6 TYPICAL SHORT DURATION PRESSURE PULSES USED (MEASURED AT STATION #3 JUST AHEAD OF THE TEST SECTION)

of fire response to blast with a simple, step pressure jump (well-defined, constant overpressure). The mean blast overpressure value for each test was obtained, as previously, by integration of the detailed blast overpressure signature measured during the test; typically, the integration (averaging) time interval is the first ~ 70 ms after shock arrival (see Appendix B), integration being terminated at the onset of rapid pressure decay.

The 1980 results with 3/4-in. stick cribs (Figs. 2 and 3) have been supplemented by new tests on 3/4-in. stick cribs, that verify the existence of the upper (high-overpressure) threshold and of the lower threshold near 1 psi. The updated figures are presented and discussed below; the new test data on 3/4 in. cribs is presented in Table B-3 (Appendix B).

Fig. 7 contains results for 3/8-in. and 3/4-in. stick cribs. Individual data points (corresponding to extinction, nonextinction, or crib posttest reignition cases) are entered for 25* tests on 3/8-in. stick cribs. The individual data points for the 3/4-in. stick cribs are not included; instead, the threshold curve (dashed line) representative of the results (see Fig. 2) is used for the comparison. Even without a suitable threshold curve for 3/8-in. cribs data, it appears that the apex of the extinction peninsula at ~ 170 s preburn time, beyond which no blast extinction is observed for the 3/4-in. cribs, is about a factor of two greater in preburn time than the rightmost extinction data point for the 3/8-in. cribs at ~ 85 s preburn time. Although the ensuing interpretation of the data on both crib types will eventually yield a slightly different relative factor between the two preburn time scales, the effect of the fineness (stick width) of the components of the fuel piles (cribs) is already apparent in the shortened event-time scale.

Figure 8 compares the two sets of data for the 3/8-in. and 3/4-in. cribs on the basis of the measured preburn crib weight loss (expressed as percent of initial crib weight). Figure 8 contains individual data points

*The cloth wick for the ignitor fluid did not function optimally in the first 9 tests, slowing ignition; with a metal frame used thereafter ignition improved. Nevertheless, the data from the nine tests correlate well with the preburn weight loss and are so used.

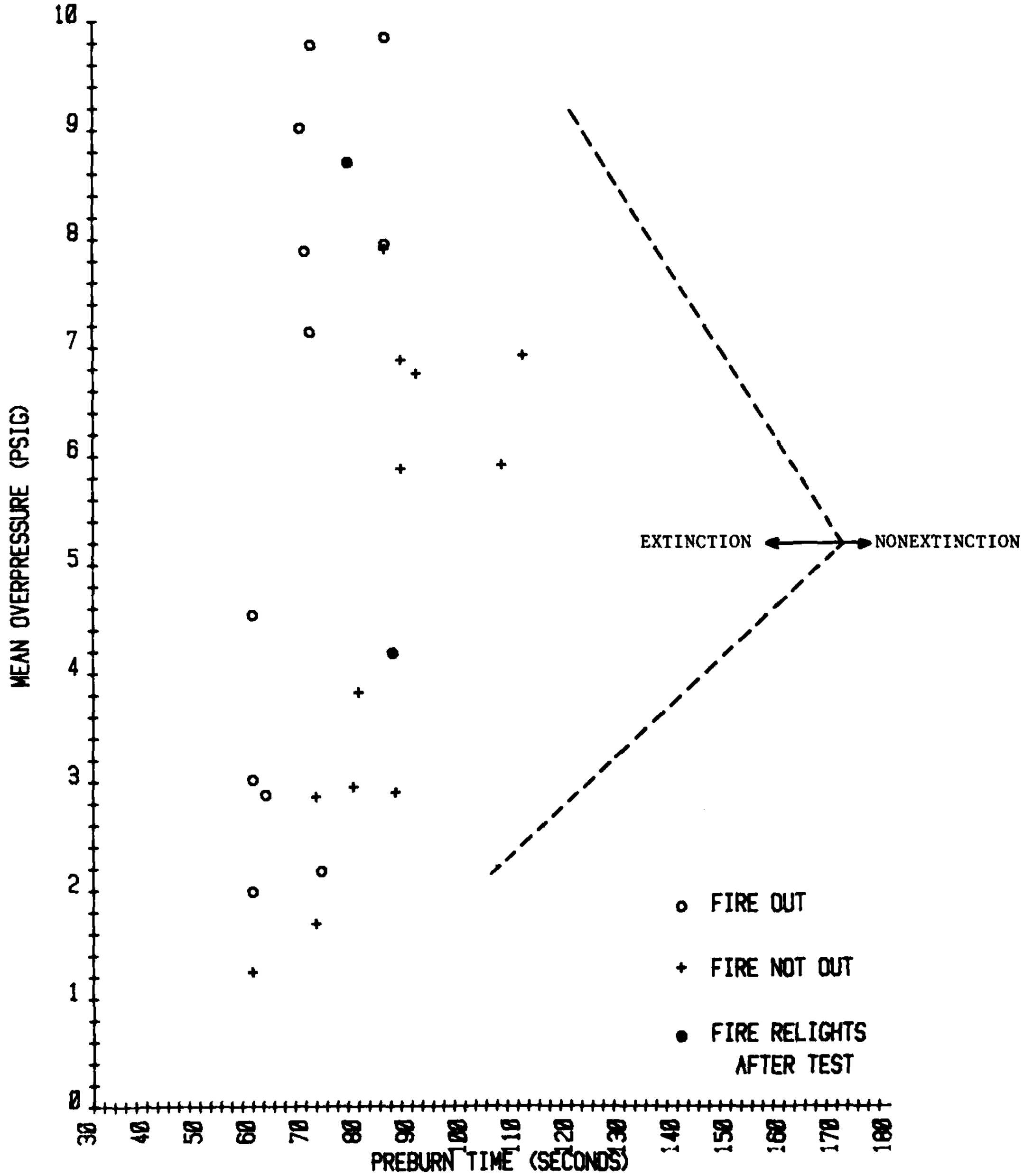

FIGURE 7 BLAST EXTINCTION DATA FOR 3/8-in. STICK CRIBS, WITH EXTINCTION-PENINSULA CURVE FOR 3/4-in. STICK CRIBS (DASHED LINE) FROM REF.1 (BASED ON CRIB PREBURN TIME)

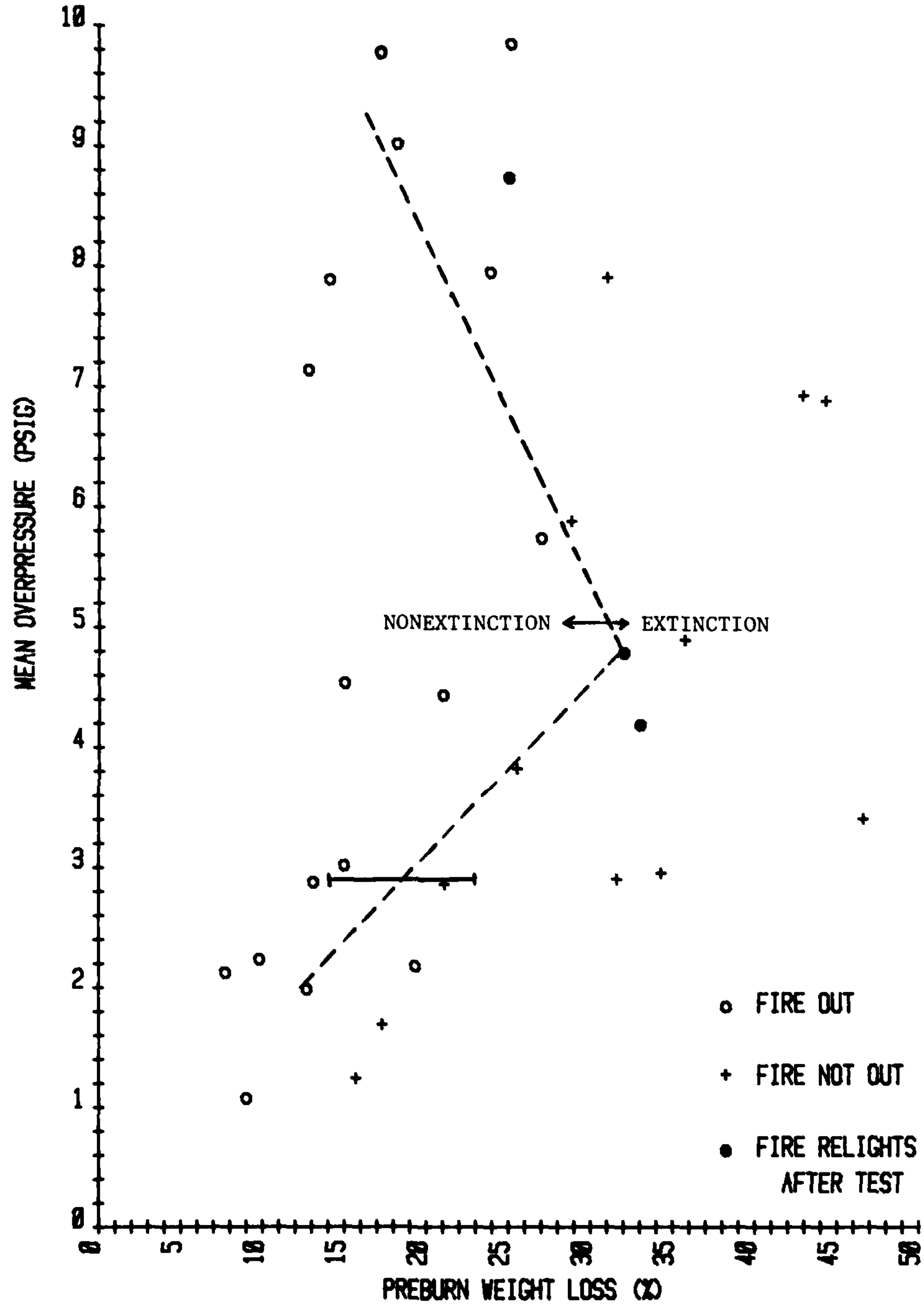

FIGURE 8 BLAST EXTINCTION DATA FOR 3/8-in. STICK CRIBS, WITH EXTINCTION-PENINSULA CURVE FOR 3/4-in. STICK CRIBS (DASHED LINE WITH ERROR BAR) FROM REF.1 (BASED ON CRIB PREBURN PERCENT WEIGHT LOSSS)

for the 3/8-in. stick cribs, but the results for the 3/4-in. stick cribs (shown completely in Fig. 3) are represented here by only the extinction peninsula curve. (The extinction and nonextinction regions for the 3/4-in. cribs are to the left and right, respectively, of the dashed curve). The lower threshold for the 3/4-in. cribs--that part of the dashed curve which has positive slope--appears to roughly correlate with the 3/8-in. crib data as well. In other words the data to the left of the threshold correspond to extinction and only one data-point to the right of the threshold is in the nonextinction region to the right of the curve, but still within the threshold uncertainty (error bar) of the lower threshold for the 3/4-in. cribs. Both data sets are reinterpreted below.

Figure 9 contains data solely for 3/8-in. cribs and the interpretation offered is based solely on those data. The first observation that can be made is that for crib preburn weight loss greater than some limiting value, no permanent extinction has been observed over the range of overpressures tested (approximately 1-10 psi). The minimum value of such critical weight loss in Fig. 9 is 28%; the apparently pressure-independent nonextinction region with weight loss greater than the critical value is denoted by dots. Two cases of crib reignition (at 4.1 and 4.8 psi) lie to the right of the threshold, within the dotted region. Another case of crib reignition is at $\sim$ 8.8 psi, but lies outside the dotted region. This point may signify one or both of the following: either there is a significant region of uncertainty around the (vertical) critical weight loss line (caused, for example, by any unevenness of the crib burning) or the point may indicate some degree of blast enhancement of charring combustion such as presumably caused the existence of the upper threshold for the 3/4-in. cribs However, no strong indication of such an upper threshold can be detected in the data for 3/8-in. cribs, although the data in that region are not be exhaustive enough to categorically exclude it.

A lower threshold for crib preburn weight loss less than 28% (and at least 9%) can be constructed from the data in Fig. 9. Or rather, three low-pressure thresholds can be drawn based on the different criteria. The uppermost threshold can be considered a conservative threshold for

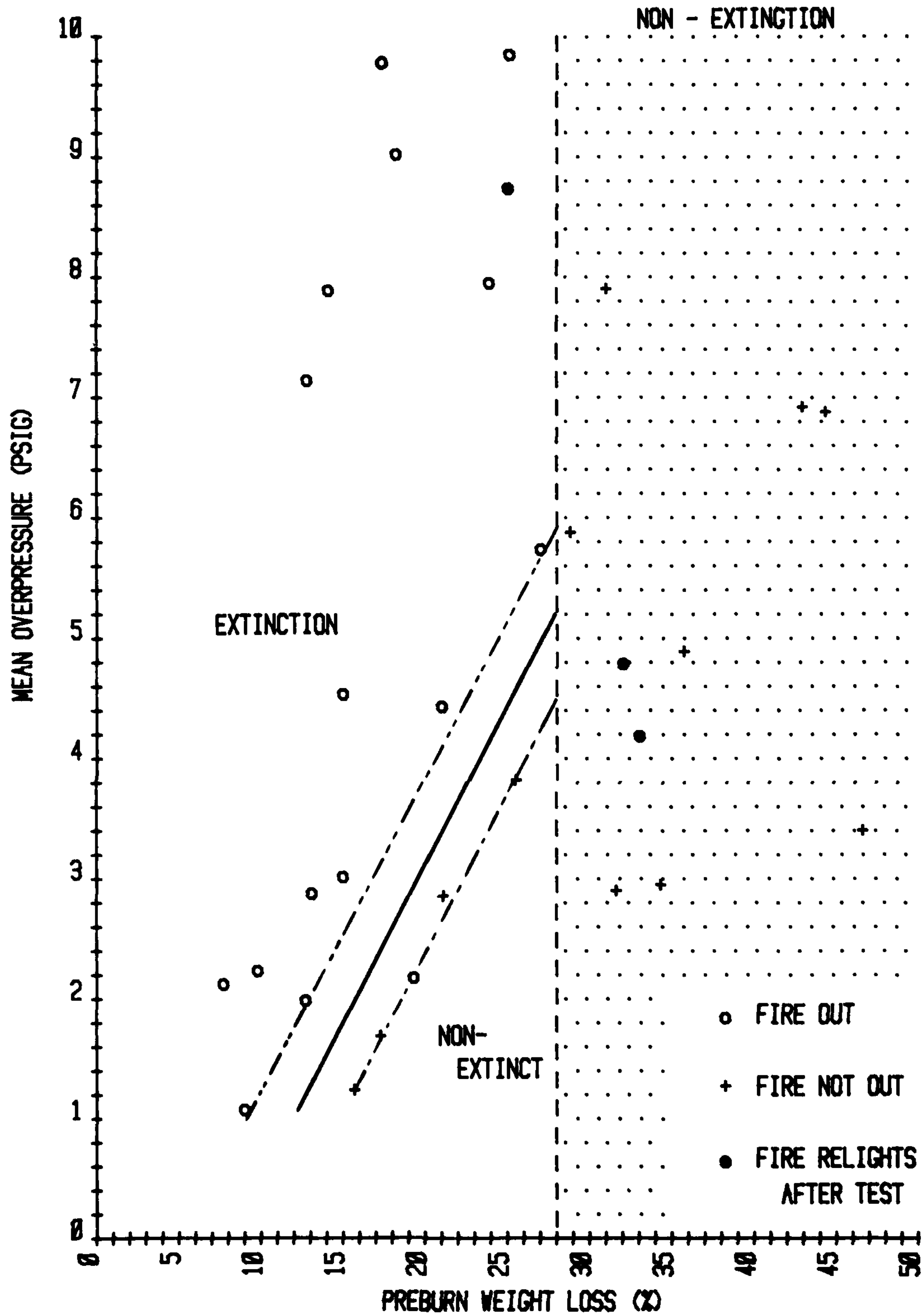

FIGURE 9 BLAST EXTINGUISHMENT OF FIRES ON 3/8-in. STICK CRIBS, BASED ON CRIB PREBURN PERCENT WEIGHT LOSS

extinction of the crib fires for less than 28% of preburn weight loss. That is, all cases to the left of the threshold line--and, with the exception of the single reignition case (at 8.8 psi), also above the threshold line--correspond to permanent fire extinguishment. The lowest threshold would be a conservative threshold for nonextinguishment, i.e., below this threshold the fire is expected to survive the blast. Between these two thresholds is where the actual threshold may lie; with a median threshold (solid line), the two extreme lines serve as error-bars to such threshold, similar to that shown in Fig. 8 for the low-overpressure threshold for the 3/4-in. cribs. Subjectively speaking, the lower threshold--having a mix of "fire out" and "fire not out" points--could, with a greater concentration of data points in that region, be closer to the actual threshold. However, some error bar would certainly still be associated with such a threshold, which is to some extent always statistical. It is not presently, and may never be, cost-efficient to obtain statistically rigorous description of the blast extinction behavior near a threshold.

Figure 10, showing the data for 3/8-in. cribs in terms of the crib preburn time, leads to an interpretation similar to that in Fig. 9. The critical preburn time, which when exceeded renders the crib fire not permanently extinguishable by blast, is approximately 85 s. (Two high-overpressure "fire out" points lie on the critical-time threshold, suggesting its statistical nature and some confidence error bar on the chosen value of 85 s.) As in Fig. 9, there is no evidence of a high-overpressure (upper) threshold for times less than 80 s. The situation at the lower threshold, for times between ~ 60 s and 85 s, is analogous to that in Fig. 9. The middle low-pressure threshold (solid line) appears in Fig. 10 to be closer to an actual threshold because it contains all "fire not out" points, whereas these fell on the lowest-positioned threshold in Fig. 9.

Figure 11 reinterprets the data for 3/4-in. cribs in a way analogous to Fig. 9. Figure 11 contains previous (1980) data as well as seven new data points obtained to clarify the lower and upper thresholds. For the 3/4-in. cribs the critical weight loss for extinction, regardless of blast overpressure, may be lower than the 28% for the 3/8-in. cribs. The value chosen in Fig. 11 or $\sim 23.5\%$, encompasses the two reignition points in

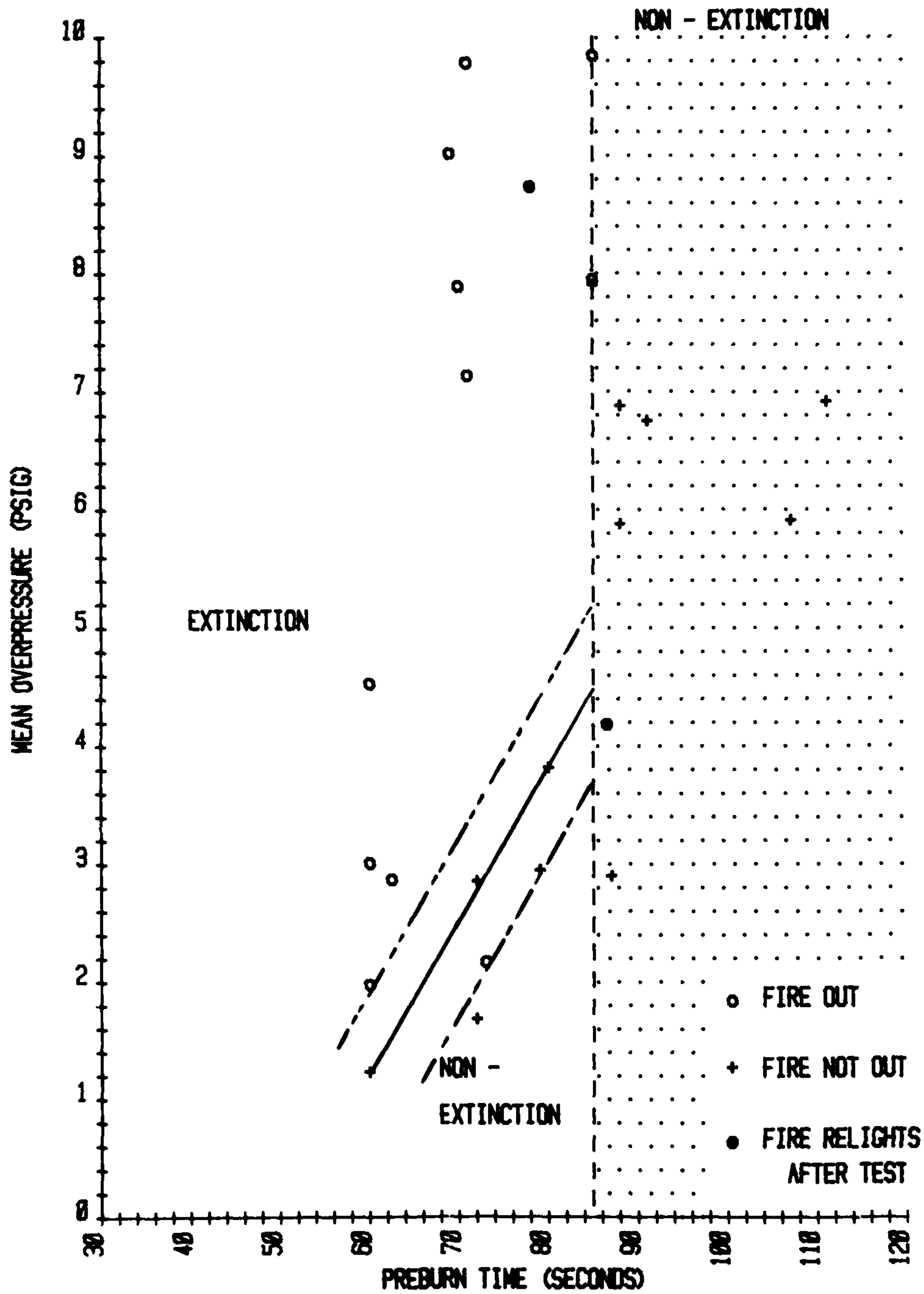

FIGURE 10 BLAST EXTINGUISHMENT OF FIRES ON 3/8-in. STICK CRIBS, BASED ON CRIB PREBURN TIME

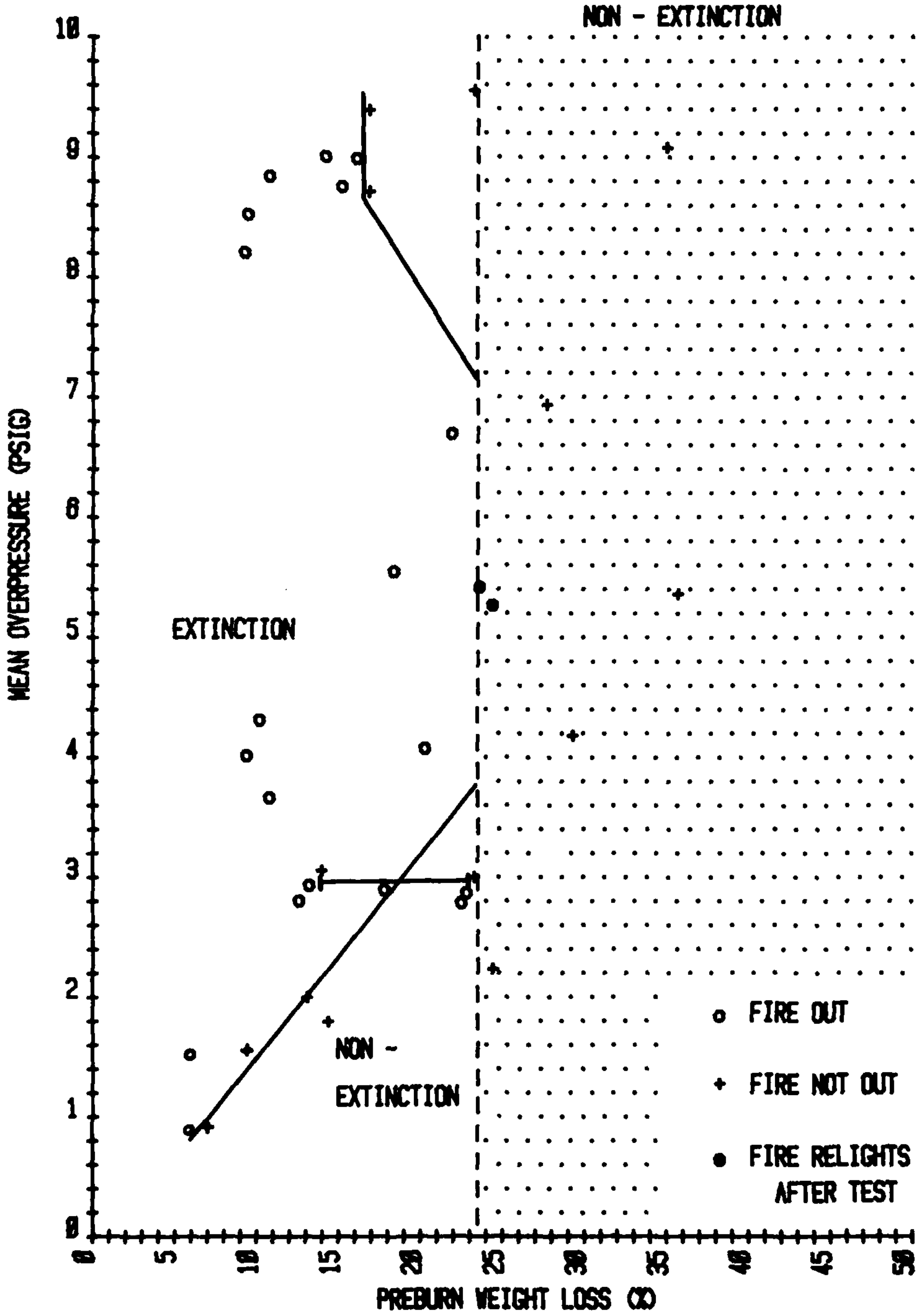

FIGURE 11 BLAST EXTINGUISHMENT OF FIRES ON 3/4-in. STICK CRIBS, BASED ON CRIB PREBURN PERCENT WEIGHT LOSS

the nonextinction region. If the two reignition points were not included in the dotted nonextinction region, then a critical weight loss comparable to the value of 28% for the 3/4-in. cribs could serve as well in that any nonextinction points (except the two mentioned) could then still be explained as part of either the lower or the upper (high-overpressure) threshold. It is best to keep in mind the possible uncertainty between 23.5% and 28% in the critical weight loss for the 3/4-in. cribs. In fact, in the 1980 report of the data (Ref. 1), the distinction between the cases of fire extinction and fire reignition (after test) had not been made, which lead to the reported wedge-shaped blast-extinction curve. In Fig. 11, the lower threshold (solid line) now extends down to just below 1 psi by the inclusion of new data around the 1 psi level. The threshold line in the 2-3.5 psi region coincides approximately with the previously-reported threshold values (Ref. 1).

At the high overpressures, three new data points have been obtained to verify the hypothesized blast-enhancement effect. This was desirable because, after the critical, pressure-independent threshold line at 23.5% weight loss (vertical line in Fig. 11) had been drawn, only one data point corresponded to nonextinction with weight loss less than 23.5%. With 2 data points now manifesting nonextinction at weight loss significantly below 23.5% (both with 16.9% weight loss) and overpressures of 9.4 and 9.7 psi, the deviation of the threshold to lower weight loss at high overpressure appears definite, although an analogous deviation has not been observed for the 3/8 in. cribs. The high-overpressure data below the critical weight loss do not immediately suggest the shape of the upper threshold curve; the curve drawn consists of a vertical cut-off line at 16.8% weight loss between 8.6 and 9.4 psi, to the left of which extinction appears likely, and negative-slope line between 16.8 and 23.8% which is essentially the previous threshold shifted down. In this trapezoidal region (if truncated at $\sim$ 9.5 psi) nonextinction has been observed and extinction cannot be counted on.

Figure 12 presents the supplemented and reinterpreted data for the 3/4-in. cribs, in terms of the preburn time. The interpretation is as for Fig. 11. Special note should be made here of the possible uncertainty of the lower threshold based on preburn time. The appreciably wide error

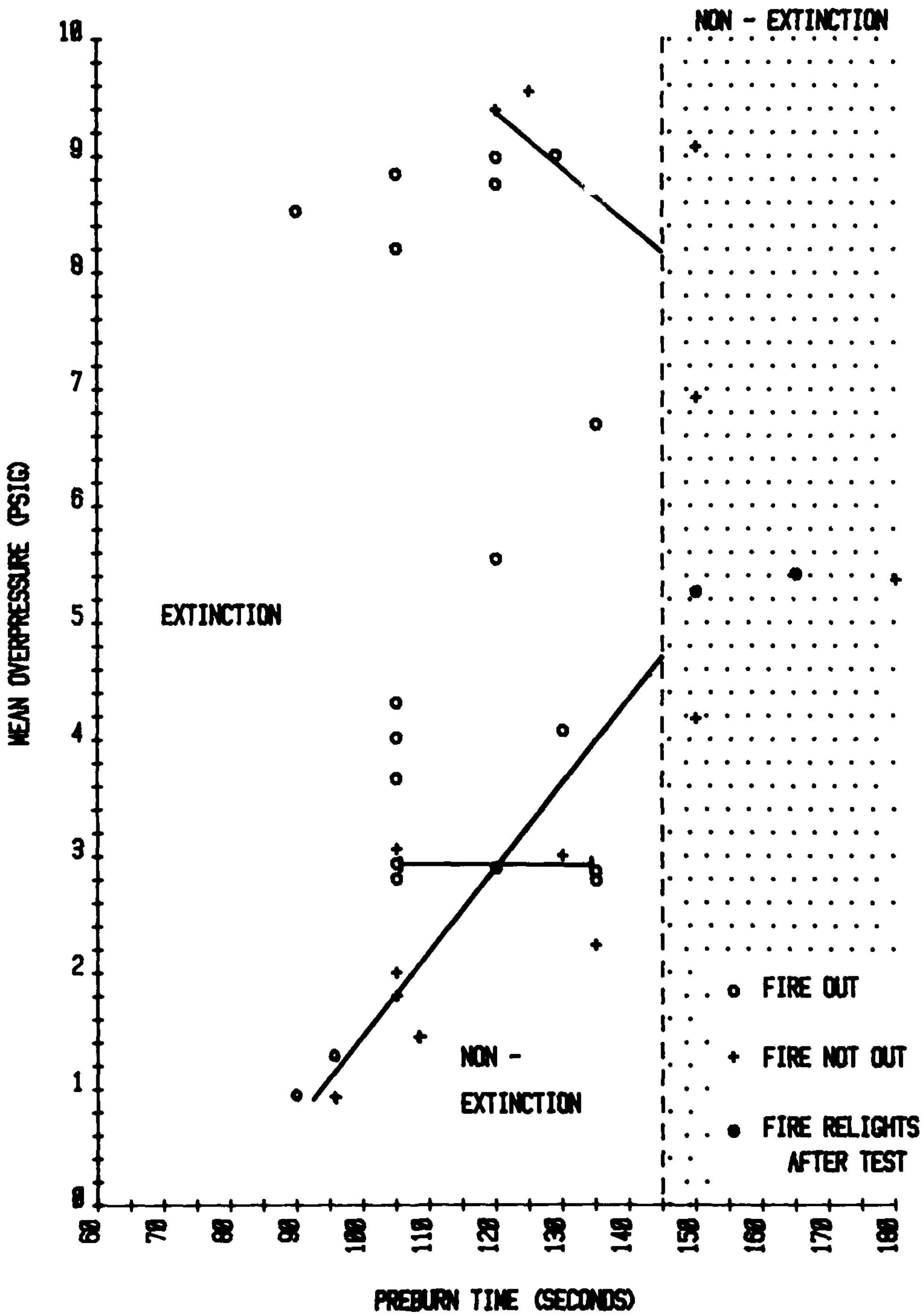

FIGURE 12 BLAST EXTINGUISHMENT OF FIRES ON 3/4-in. STICK CRIBS, BASED ON CRIB PREBURN TIME

bar (shown at the 3 psi level) may extend down to the 1 psi level on evidence of the two extinction points below the threshold near 1 psi.

The interpretation of threshold data is concluded here by two figures (Figs. 13 and 14) that show a strict interpretation of the extinction and nonextinction boundaries for the two types of cribs. Although drawn subjectively, the two curves in each figure are drawn such that on one side of each curve there is a region of either all-extinction or all-nonextinction cases.

In Fig. 13 for 3/8-in. stick cribs, curve 1 is drawn such that to the left of it there are only cases of complete, permanent extinction ("fire out" points, marked o); curve 2, on the other hand is drawn so that to the right of it there are only cases definitely not put out by blast (eventual reignition cases, marked •, are excluded). Curves 1 and 2 in Fig. 14 for 3/4-in. stick cribs are drawn by the same definitions. Based on the present data, therefore, the region of greatest confidence for blast extinction is to the left of curve 1 and the region of greatest confidence for the ability of fire to withstand blast unextinguished is to the right of curve 2. The shape of the curves for the two crib types is similar, but they are shifted toward greater percent weight loss values in the case of 3/8-in. cribs, as shown in Fig. 15. It must be remembered that Figs. 13 and 14 as well as all other figures discussed above are based on data for wood cribs ignited by alcohol and subjected to short-positive duration airblast such as those pressure pulses shown in Fig. 6. Conjectures about the behavior under other conditions and with other charring materials based on these findings must still be verified.

Discussion

While maintaining the same overall crib dimensions, for the present tests the cribs used in the 1980 tests were scaled down in their element size by a factor of 2 to determine the relationship between extent of burning and material thickness. For a unit amount of crib surface area, the steady-state burning rate (weight loss rate) empirically depends on the inverse square root of the fuel element (stick) thickness, increasing specific burning rate for the half-size-stick cribs by 41%, thus shortening

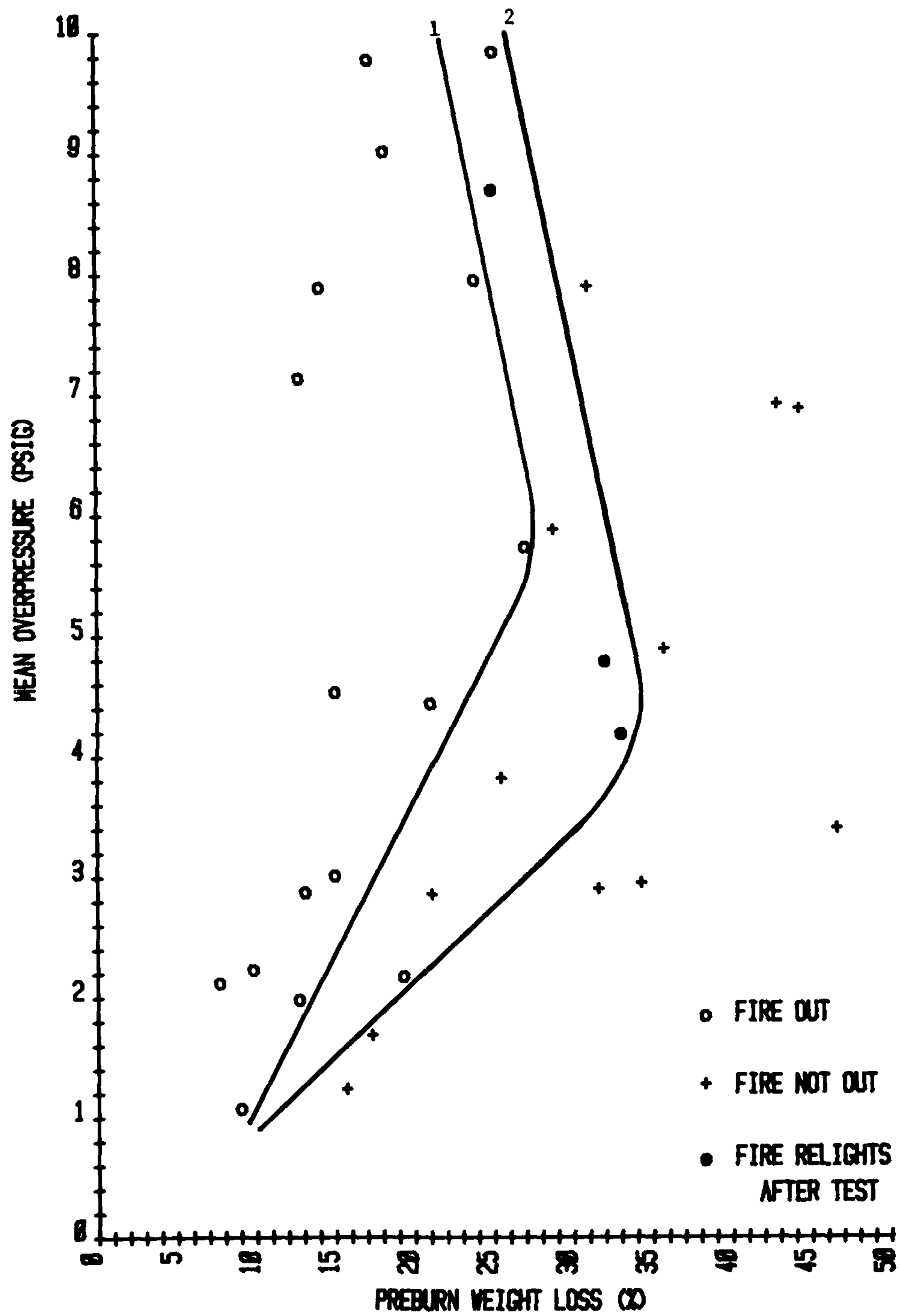

FIGURE 13 STRICT EXTINCTION/NONEXTINCTION BOUNDARIES, 3/8-in. STICK CRIBS

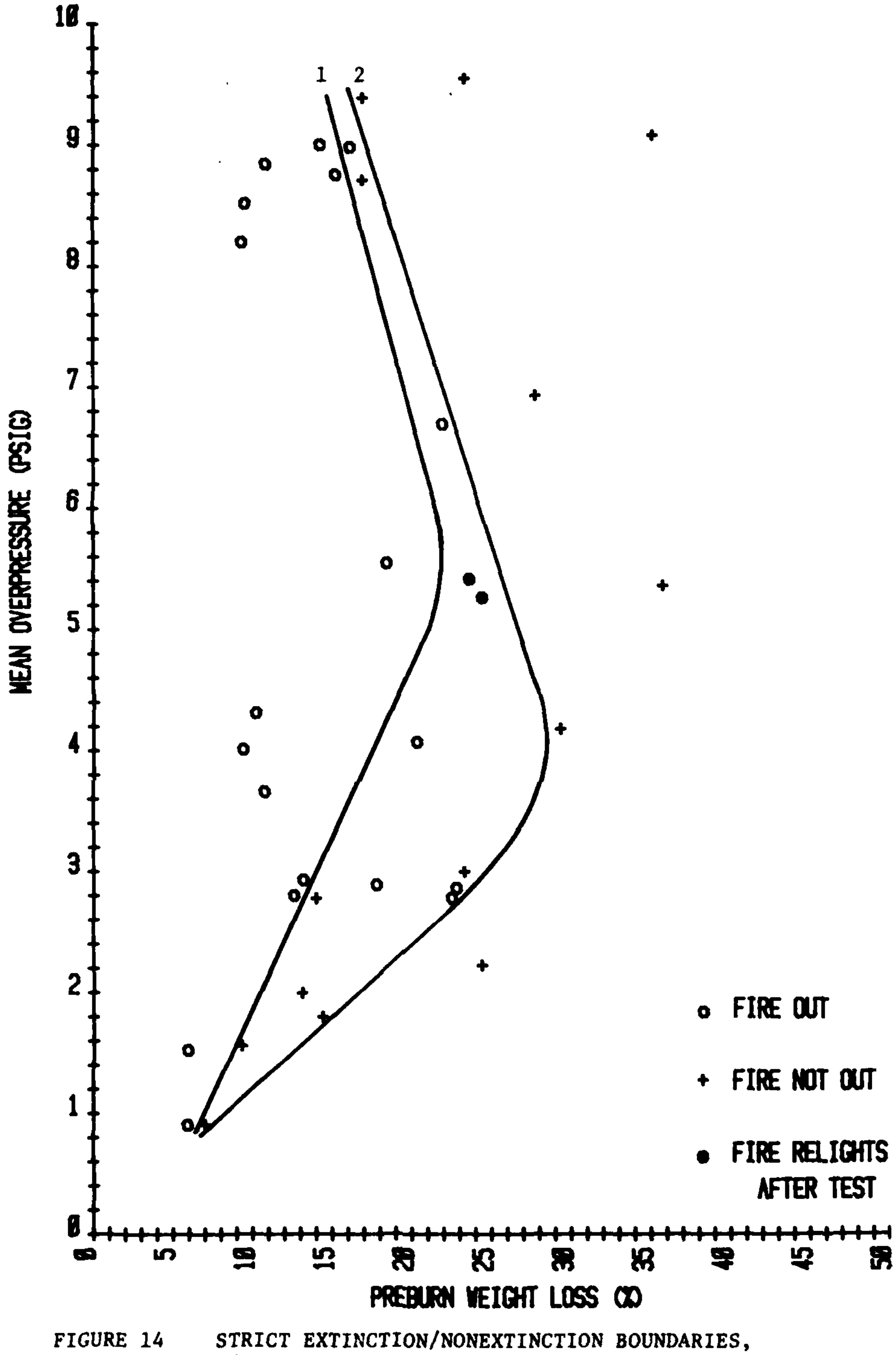

FIGURE 14 STRICT EXTINCTION/NONEXTINCTION BOUNDARIES, 3/4-in. STICK CRIBS

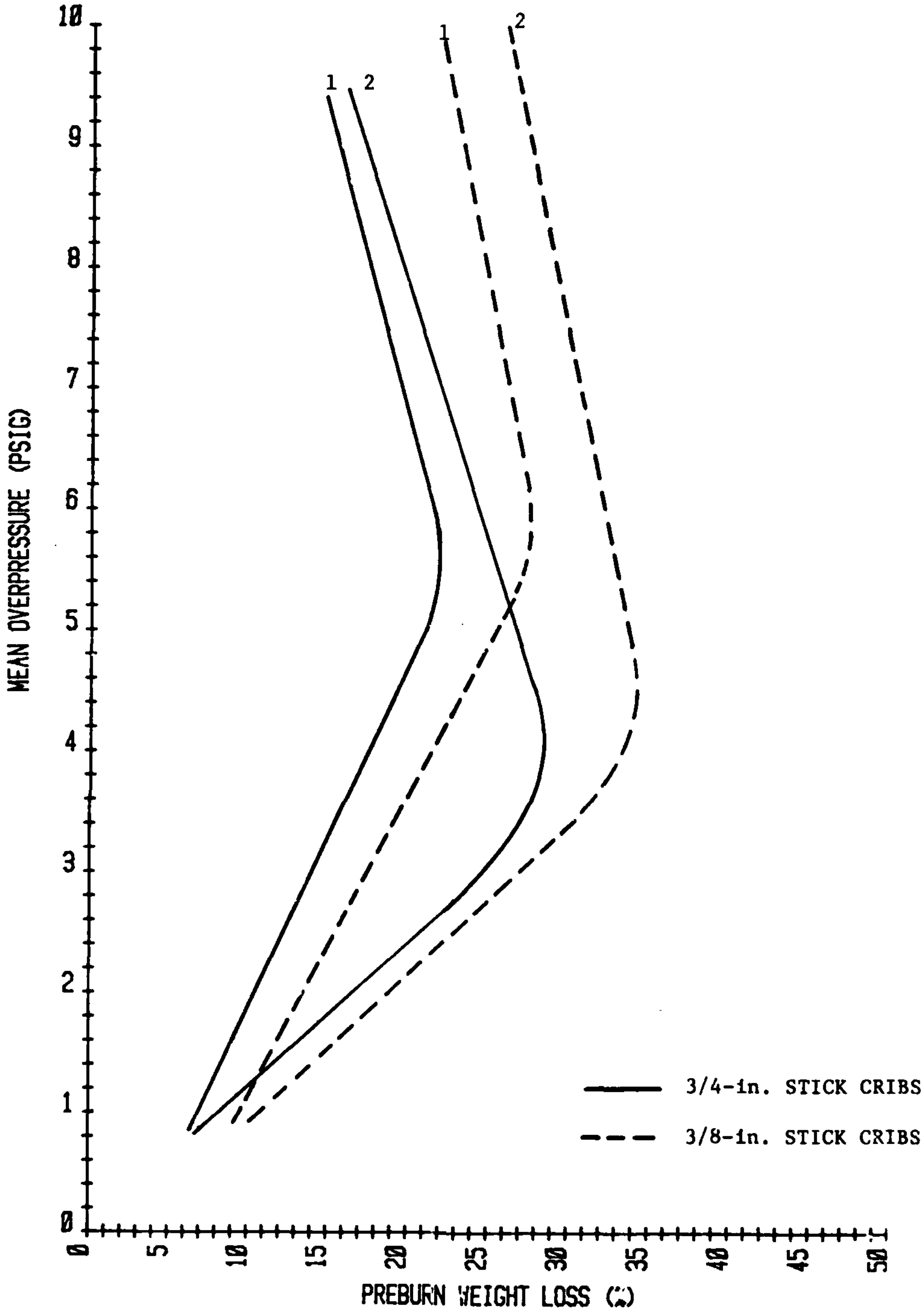

FIGURE 15 STRICT EXTINCTION/NONEXTINCTION BOUNDARIES FOR BOTH CRIB TYPES

the fire time-scale by 30% (during steady burning a correction must account for the initial burning transient).

This shortening of the time scale was well confirmed by experiments with the new cribs. Comparison of the limiting preburn times (limit of extinguishability by blast) suggests a 40% reduction in time scale. Both crib types became unextinguishable when comparable percentage weight loss occurred (23.5% and 28% for the 3/4 and 3/8-in. cribs, respectively) and correlations of extinction thresholds in terms of percent crib weight loss were very similar (but did not exactly coincide).

Ultimately, we wish to extend the time-scaling concept to the full weapons effects simulation (including thermal source), which also models the actual time lapse between thermal pulse (with ignition) and shock arrival. For example, with a hundred-fold reduction in fuel-element thickness, to 7.5* mils, the limiting preburn time would hypothetically be 10-15 s; this lies between the airblast arrival times of 8 to 9 s at a 10-cal/cm^2 station for a 100 kt weapons and 22 to 24 s at a 10 cal/cm^2 station for a 1 Mt weapon. (10 cal/cm^2 would be sufficient to ignite 7.5 mil-thick cellulosic materials.) However, such conceptual (and quantitative) extrapolations need to be refined and verified in the shocktube (with the use of the thermal source).

Moreover, the extinction overpressure thresholds for preburn times shorter than the limiting time can at present be only approximately inferred from such extrapolations. Hopefully, shocktube data will also provide us with generalizable relationships between extinction overpressures and preburn times that are predictable from the physical and chemical characteristics of the ignited fuel elements. Noncellulosic (and noncharring) materials must also be extensively examined.

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*An element thickness of 7.5 mils (0.019 cm) is in the range of common urban interior combustibles. Newspaper has a sheet thickness of about 0.008 cm; drapery-weight fabrics are often 0.03 cm and thicker.

III CLASS-B FUEL TESTS: EFFECTS OF FUEL TYPE

Previous Shocktube Experiments Using Class B Fuels

Two types of fires have been tested extensivelv for airblast extinction behavior (Ref. 1 and 2): (1) liquid-fuel pool fires of various sizes; (2) liguid-fuel pool fires, of various sizes, with flow-obstructing barriers upstream of the pool fire. These are described briefly below. Other limited tests (Ref. 2) included the effects of fuel bed surface roughness (little effect was found even with rough gravel beds) and the role of airblast positive phase duration (great reduction of extinction overpressure thresholds as duration increases was suggested by the few tests conducted).

Pool fires

n-Hexane and methanol pool fires of 1, 2, and 3-ft fuel bed length (10 in. wide) were tested for extinction thresholds. The mean blast overpressure required for permanent fire blowout was found to increase as the bed length--i.e., the scale of the fire--increases. Film records demonstrated rapid flame displacement by blast. Based on the threshold (mean) overpressures, the calculated critical displacements of air particles above the fuel bed correspond, in the absence of fire, to a constant multiple of the bed lengths (5.5 to 6 times the fuel bed length). At the largest scale tested, the 3-ft fuel bed, the hexane fires were found to withstand, unextinguished, a blast of up to 5 psi. Methanol, on the other hand, was extinguished on the 3-ft bed by blast of mean overpressure as low as 1.1 psi.

Flow Barrier Effects on Fire Blowout

With an L shaped, 1 3/4-in. high flow barrier positioned 3 1/4-in. upstream of the pool fire, the disturbance by the barrier of the aftershock flow was found to effectively elevate the mean threshold overpressure required to extinguish the fire at each fire size; essentially,

the hexane extinction threshold was shifted upward by 1 psi. Photographs of particle-laden after-blast flow (without fire) showed the extent of flow deflection by the barrier and a region of reverse flow behind the barrier; film coverage (with fires) indicated fuel reignition to occur in the large eddy behind the barrier, showing its function as a flame-holder.

With the barrier, a 3-ft methanol fire was sustained at 1.1 psi (compare with hexane threshold of about 6.1 psi). The experiments with barriers demonstrated the strong and complicated effects of nonflat and flow-perturbing geometries on fire extinction; they pointed to the limited practical applicability of flame-displacement as a basis for theoretical development and to the need for phenomenological investigation.

Purpose of Present Tests

Using, as a basis and reference, the results and understanding obtained from previous (1979, 1980) shocktube tests with class B (liquid) fuels, the present tests investigated the effect of fuel type and how it compared with other effects previously studied and discussed above.

The aim was to answer such questions as:

- What physico-chemical fuel properties or burning parameters appear to correlate blast-extinction behavior best; specifically what is the role of fuel volatility and fuel flash point and boiling point?
- Are the extinction thresholds of most common flammable or combustible liquids closer to the low values of methanol or the relatively high values found for hexane fires?
- Can the behavior be divided by class--do alcohols, paraffins behave alike within a group and distinctly from other fuels?
- Are the extinction thresholds of various common liquid hydrocarbons--perhaps industrially the most widely used flammable liquids--similar enough to hexane data that hexane can be used as a model hydrocarbon in most blast extinction problems?
- What other common fuels are as easily extinguishable as methanol, posing a significantly lesser danger of fire persistence after blast than similar hydrocarbon fuels?

In addition, data on liquid fuels whose fires are of intermediate resistance to blast relative to the known extremes of hexane and methanol are needed so that parallel analytical efforts are aided by a greater range of data. Several class-B fuels were tested, in hopes of answering the above questions.

Fuel Selection and Preburn Conditions

As described in the preceding section, flammable and combustible liquids (including industrial liquids), such as hydrocarbons, were of main interest, serving as both model fuels and common liquids.

The hydrocarbons pentane, hexane, and kerosene vary widely in their molecular weight with pentane < hexane < kerosene. Their boiling points follow the same trend; a very useful range of boiling points from 36°C (pentane) to 250°C (kerosene) is thus represented. Physically, the effective fuel volatility--or the heat required to gasify a gram of fuel--essentially controls the vigor of fuel vaporization and "fire intensity" for a given fire size. The latent heat* for fuel at boiling point is identical for pentane and hexane, but differs as the fuel temperature deviates from boiling point (see L and L_{eff} in Table 1). Kerosene has latent heat at boiling temperature actually lower than that of pentane or hexane, but for fuel initially at 20°C the effective latent heat of kerosene is much higher due to its high boiling point. Acetone, a ketone, was chosen as a comparison fuel for its different chemical structure and properties that spanned the range of hexane, pentane, and kerosene. Table 1 summaries the properties of the new chosen fuels (pentane, kerosene, and acetone), as well as of the previously tested fuels (hexane and methanol).

The fuels were tested on the 3-ft long fire bed (35 1/2-in and 9 1/4-in M-board substrate) in the flat-plate, zero-angle of incidence configuration. The preburn time for kerosene and acetone was 15 s, as used previously for hexane. For pentane, the preburn time was reduced to 5 s.

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*per unit mass of fuel.

Table 1

FUEL PROPERTIES AND EXTINCTION BLAST OVERPRESSURES

Fuel	Extinction overpressure (psi)	M (g/mole)	T_B (^oC)	Flash Pt. (^oC)	L (cal/g)	L_{eff} (cal/g
n-Hexane	5.2	86.	68.0	-17.7	87.1	113.
n-Pentane	2.8-3.0	72.	36.0	<-40.	87.1	96.
Kerosene	1.5-2.0	~154	250.0	37.8	69.5	176.
Acetone	1.5-1.9	58.	56.7	11.1	125.0	149.
Methanol	<1	32.	64.5	-21.7	263.0	288.

Notes:

o.p. = Mean blast overpressure threshold (short positive-phase duration airblast) for 3-ft fuel beds

M = Fuel molecular weight

T_B = Boiling temperature of fuel at 1 atm

L = Fuel latent heat (heat of vaporization) at boiling point

L_{eff} = $L + C_{p\ell}\ (T_B - T_R)$ effective latent heat for fuel initially at $T_R = 20^oC$; includes heating of fuel to boiling point: $C_{p\ell}\ (T_B - T_R)$ ($C_{p\ell}$ = liquid fuel heat capacity)

Extinction Thresholds: Data Interpretation

The series of shocktube tests with kerosene, pentane, and acetone includes 15 tests. The test data are summarized in Table B-1 (Appendix B). All 15 tests used short positive phase duration pressure pulses, such as were shown in Fig. 6 in Section II. The extinction overpressure threshold values obtained from the tests are shwon in Table 1 for ready comparison with the test fuel properties.

The unusually high gasification heat requirement for methanol, included in 1980 tests, made it a low intensity and easy blow-to-blow-out fire compared with hexane (which requires less than half the gasification heat of methanol). Thus the kerosene fire (with a gasification heat requirement more than 60% greater than hexane for fuel initially at ambient temperature) was expected to be more easily blast-extinguished than hexane--and it was. The extinction threshold of kerosene lies between 1.5 and 2.0 psi, while the corresponding hexane threshold was at about 5.1 psi. However, the pentane fires were about as easily extinguished as kerosene, with the threshold for pentane being in the range of 2.8 to 3.0 psi; that is, pentane was significantly more easy to extinguish than hexane, although a higher threshold was expected for pentane than for hexane due to pentane's lower effective heat of gasification for any vaporization temperature below boiling point (at boiling point their latent heats are equal). The third fuel tested this year, acetone, was more easily blown out than hexane, at surprisingly low overpressures--even lower than for kerosene. The acetone threshold was between 1.5 and 1.9 psi.

No trends in the extinction thresholds are apparent with respect to the fuel boiling points, flash points, or molecular weights shown in Table 1. With the exception of hexane, the fuel latent heat correlates with the extinction thresholds, and this correlation would hold even for significant deviation in heat of gasification from the latent heat (measured at boiling point). Roughly any heat of gasification for vaporization temperature between the boiling point and the midpoint between boiling point and ambient temperature (20°C) would adequately correlate the results--save for the high hexane threshold.

The limited insight gained by the overpressure threshold data alone is much expanded by the information obtained from high-speed camera coverage.

Film Records

The high-speed camera recording of observable events is described in Ref. 1. The camera framing rate at shock arrival was about 1600 frames/s in the tests with Class B fuels. The field of view of the recorded events spans the middle 1-ft section of the 3-ft fuel bed.

The arriving shock strongly intensifies the flame luminosity and turbulence as it passes through the flame, making even relatively "red" flames like kerosene's "white-hot." Flame motion starts with shock passage and continues in all cases (even for 1 psi shock)until all flame has been swept clearly out of view. The times of flame removal from the fuel-bed middle section after shock arrival are shown in Table 2 for cases with overpressures just above and just below the extinction threshold. In the case of kerosene, the early, rapid displacement of the yellow luminous flame is followed by residual red flame (luminous vapors) very near the fuel bed; the removal time of the residual red flame is also shown in Table 2 (numbers in parentheses).

The flame flashback is observed in the near-threshold cases to occur at times $\geq$ 100 ms after shock arrival for the fuels tested, which corresponds essentially to the end of the blast overpressure positive phase. In some cases the flashback occurs through combustion on droplets, and often the first flashback does not immediately reestablish steady burning, which may occur at 200-300 ms. The film footage of the essential events from the 8 tests listed in Table 2 has been assembled in a videotape documentary.

Video-Tape Highlights of Shocktube Tests

The high-speed camera coverage of the blast/fire interaction events in the shocktube tests has been invaluable in yielding qualitative information on the observable phenomena as well as quantitative indication of the observed event times. The presentation to the concerned scientific

community of this wealth of information (there is a film record of each test), even in selected highlights, has been marred by the high framing rates (at normal projection speed, the events occur too fast to permit effective viewing). A pilot video tape has been made, which synthesizes film coverage and factual information on tests with class B fuels. Most of the material comes from the fall 1981 test series. The tape presents frame-by-frame developments of crucial events such as flame blowoff and flame flashback, with documentation. A sound track can be added at a later time. The tape runs 17 minutes (19 minutes when fully completed); it has been recorded cooperatively with SRI Video services. It is planned for presentation at the 1982 Asilomar Conference.

Table 2

INFORMATION FROM HIGH-SPEED CAMERA RECORDS

Test No.	Fuel	Fire Out?	Mean Overpressure (psi)	Flame Blowoff (ms)	Flame Flashback Start (ms)
33*	n-Hexane	Yes	5.8	8	—
34*	n-Hexane	No	4.0	12	~ 100
10	n-Pentane	Yes	3.04	16	—
9	n-Pentane	No	2.80	18	~ 133
2	Kerosene	Yes	2.06	14(36)†	—
4	Kerosene	No	1.49	18(48)†	~ 137
13	Acetone	Yes	1.94	15	—
15	Acetone	No	1.43	18?	~ 200

*1980 tests (Ref. 1)

†Time for residual red flame to disappear

Discussion

The shocktube experiments provided some surprising new information on the extinguishment behavior of various class B fuels. The surprising aspect of these tests was the relatively low extinction blast-overpressure thresholds observed for the fuels tested: kerosene (1.5-2.0 psi mean overpressure); n-pentane (2.8-3.0 psi); acetone (1.5-1.9 psi).

A conjecture concerning the effect of fuel volatility (is it important in blast extinction of class B fuels?) has been partially borne out although the high overpressure threshold of hexane still cannot be explained.

High-speed photographic evidence of the mechanism by which volatile fuels resist blast extinction in the shocktube tests puts the flame displacement mechanism into better perspective.

In a typical class B fuel shocktube experiment, the arriving shock clearly and rapidly displaced the flame off the fuel bed and swept it downstream at near the particle velocity of the airblast. The displaced flame survives downstream of the test section for up to 150 ms--or the full extent of the positive phase duration in short-duration tests. The displaced flame becomes essentially a wake flame and is fueled by vapors swept from the still-volatilizing fuel bed. The intense, turbulent mixing of the fuel-vapor/air mixture and the hot combustion gases in the shear mixing layer downstream of the fuel bed and of the test stand (rather than flow recirculation as in the case with flow obstacles) substantially increase the fuel burning velocity. When the particle velocity drops near the end of the positive phase, the high burning velocity provides for flashback upstream to the fuel bed and for eventual reestablishment of flame of the fuel bed.

Fuel volatility plays a part in the amount of fuel vapor supplied to the wake: if the fuel volatility is low, the mixture in the wake is lean and the burning velocity drops too low for combustion to persist until flow particle velocity decreases sufficiently for flashback.

If this apparent mechanism corresponds to reality, does it mean that the experiments are too non-ideal? When considering that question one must bear in mind three things: first, that even on idealized, infinite surfaces a turbulent mixing boundary layer eventually develops; second, that in the real-world blast environment, mixing by shear and recirculation in wakes would exist almost everywhere in the blast flowfield; and third, that with other fuels, such as class-A materials, other considerations--such as fuel charring--enter. However, it is apparent that, whether considered too idealized or too nonideal, the unexpected results show that we still cannot dependably predict the blast extinction thresholds of simple class-B pool fires. Nevertheless, we are gaining a clearer definition of the basic blast/fire effects categories and situations, and are cognizant of the basic governing mechanisms pertinent to each.

IV DEBRIS FIRE TESTS: PREPARATION FOR MILL RACE

The MILL RACE event was initially viewed as an opportunity to verify in the field conclusions drawn from shocktube data. In anticipation of a thermal pulse accessory to the shocktube, it appeared feasible to attempt a direct simulation of MILL RACE conditions: the expected sequence of thermal ignition followed by blast interaction could be essentially duplicated with closely matched characteristics in the simulated events (e.g., ignition-to-airblast-arrival delays, airblast durations and overpressures). As it turned out, the SRI simulation was (and still is) deficient in two important respects:

(1) Lacking the SAI thermal pulse accessory, the facility is limited to tests of airblast blowout of fires started by relatively low-power application methods and long preburn times.

(2) The available short-positive-phase-duration airblast (i.e., less than about 300 ms) is a flat-topped pressure/flow wave whose only unambiguous pressure characteristic is the duration-averaged value. Accordingly, its pressure-time integral (i.e., impulse) is expected to bear a different relationship to particle displacement than the pressure-duration product of the MILL RACE airblast. In particular, (a) when the average pressure in the flat-topped wave is comparable in value to any given MILL RACE peak overpressure, we expect the simulated early-time flow to be more intense and (b) when their durations are also comparable, the particle displacement at MILL RACE will be substantially less, all other factors being equal.

Given these deficiencies, it appeared to make little sense to invest a substantial experimental effort in attempting to predict MILL RACE outcomes before the event. Therefore, a minimal effort was given in the shocktube to ensure that fires in the shredded filter paper debris could be extinguished at overpressures of about 7 psi and that the threshold would be very roughly in the assigned "ballpark" of 3.5 to 7 psi. Further insights were sought by a review of the UCLA study of the 1950s (Ref. 5), in which the simulation did have a thermal source.

Below we report briefly the shocktube results, and describe the rationale for the design of the MILL RACE fire tests.

Debris-Fire Blowout Experiments

Twelve tests were run in the shocktube on cellulosic fuel debris beds (see Table B-4 in Appendix B).

In the first nine tests, shredded cellulosic blotter paper (0.25-in.-wide strips, 0.022 in. thick) was used in 2-ft long pans and in 6 in. by 10 in. trays; in the last three tests shredded cellulosic filter paper (0.022 in. thick) was used in 6 in. by 10 in. trays. A swing-down propane burner was used to ignite the fuel; the debris in trays was repeatably and effectively ignited with a 7-s burner time, and a total preburn time of ~ 15 s before shock firing. It was planned that at least as adequate ignition would be achieved with the TRS at MILL RACE.

After blast, the flames on the trays were displaced (blown off) down to the 1-psi level, whereas residual smolder and rekindling varied with the blast overpressure, for the same ignition conditions. For low overpressures (up to 3.5 psi) there was residual smolder, with much less significant residual smolder at 7 psi. The blotter paper (used in the first nine tests) supported smoldering more readily than the filter paper and was easily rekindled from sufficient residual embers; the filter paper was not rekindled at 3.5 and 7 psi, but the fire did not go out at 1.75 psi. From high-speed film coverage, the decrease in residual embers at high blast strengths is identified as bodily loss of embers downstream by physical removal (firebrands); thus this process contributes to any other mechanism of active ember loss (such as air cooling).

Therefore, at the low overpressures (below ~ 3.5 psi) a well-ignited fire on a thin-fuel arrangement, such as the shredded filter paper fuel beds, was expected to very likely rekindle even when a blast completely displaced the flame from the fuel bed.

Design of the MILL RACE Fire Tests

The data of Tramontini and Dahl (Ref. 5) appeared to be our best (if not only) basis for predicting airblast extinction at MILL RACE. These data show a regular, and fairly strong, dependence of extinction thresholds on both preburn time and positive-phase duration.

In his shock tunnel study of airblast extinction (at the Ft. Cronkhite facility) Goodale argued that the previous UCLA study was flawed by its failure to reproduce the pressure pulse in its entirety; that is, except for an initial, very brief shock, the duration of the blowdown flow in the UCLA apparatus was accompanied by little if any overpressure. The UCLA study assumed that pressure, per se, was unimportant to the blowout effect. To date, this assumption remains unsubstantiated. Preliminary data from our concurrent study, funded by DNA, indicates important differences between shocked and unperturbed air in the extinction of fires over volatile-fuel wetted wicks, which we tentatively associate with pressure-jump induced turbulence. This difference notwithstanding, the presence of a shock in the UCLA blowdown may be all that is required for adequate simulation; their data may prove to be quite valid. We have adopted this hopeful view in attempting to predict blowout threshold for the MILL RACE event.

MILL RACE conditions fall within the range of the UCLA test variables: peak velocities, flow durations (and the associated decay rates in flow)*, preburn times, fuel bulk densities and moisture contents, even fuel element thickness and other physical and some chemical properties. If the UCLA simulation was indeed adequate, then the only obvious difficulty is that the UCLA study did not include shredded filter paper. The only paper was crumpled newsprint. The only wildland fuel of comparable element dimensions and spacings appears to be pine needles. Weathered ponderosa pine needles were extensively studied in the UCLA work. From their data, Tramontini and Dahl derived the following empirical expression:

$$V_o^* = \theta_F^{-0.413} M^{-0.125} (7.93\theta_B - 16.8D + 157)$$

with no significant difference between vertically and horizontally oriented specimens.

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*The relationship between velocity and time (i.e., flow decay rate) is approximately:

$$V(t) = V_o\left(1 - \frac{t}{\theta_F}\right) \text{ for } 0 \le t \le \theta_F$$

The variables are:

V_o^*(ft/s) = threshold peak particle velocity for extinction

θ_F(s) = flow duration

θ_B(s) = preburn time

D(lb/ft^3) = bulk density

M (%) = moisture content

With modest changes in the numerical values of the coefficients and exponents, the expression can be made to fit all of the UCLA data reasonably well.

If we group the variables characterizing the air blast wave on the left-hand side of the equation; that is

$$V_o^* \theta_F^{0.413} = M^{-0.125}(7.93\theta_B - 16.8D + 157)$$

we are left with variables characterizing the fuel and its preburn time on *the right. This suggests* the general approximation

$$V_o^* \theta_F^{0.4} = C\ (\ell,\ k,\ \rho,\ C, \ldots M,\ \theta_B)$$

For a given fuel (i.e., constant k, ρ, c) at a constant moisture content and preburn time, C becomes a function of ℓ only:

$$V_o^* \theta_F^{0.4} = C\ (\ell)$$

from which a separate empirical expression C(ℓ), showing the dependence of the blowout threshold airblast characteristics on material (element) thickness, can be evaluated from the UCLA data on materials of common chemical and intensive physical (thermal) properties, fixed moisture contents, bulk densities and preburn times. We attempted this, but were unable to discern any regular dependence of C on thickness. Therefore, the scope of applicable data was expanded by including experiments under dissimilar conditions and using the approximation

$$C = M^{-1/8}\left[8\theta_B - 17D + E(\ell)\right]$$

to correct for effects of the moisture, bulk density, and preburn variations. All dependence of C on ℓ is assumed to be contained in the variable $E(\ell)$. Again we could find no distinct, systematic dependence of E on ℓ; the midrange value E = 142 was crudely representative of all materials. There seemed to be a slight trend of increasing E with increasing ℓ, which could lead to a somewhat higher estimate of E for the shredded filter paper, perhaps 200 or more, but there is scant justification in these data for choosing the higher values.

Using E = 142, we then calculated values of C for two different moisture contents (4% and 10%), two different bulk densities (3.2 and 2 lb/ft^3), and the anticipated range of MILL RACE preburn times (2.5 and 4 s). The published values of θ_F, at various distances from the MILL RACE GZ, were used to calculate V_o^* values and these were compared to the published peak overpressure estimates at the corresponding distances. These are shown graphically in Fig. 16. (Actually, the corresponding peak particle velocities are shown in Fig. 16.) The results imply that all edge-on targets may be extinguished, at 3.5 as well as at 7 psi.

Adopting the higher estimates of E (e.g., 200) brings the thresholds into better position for obtaining a bracket in the edge-on targets. There is very little comfort in this result, however, because we have almost no reason to adopt these higher values. It appears important, therefore, to keep both moisture contents and bulk densities at the lowest practical levels available. Even then, we may obtain bracketing results only in terms of the angle of incidence at one or both overpressures.

The apparent lack of dependence of blowout response on element thickness deserves a careful scrutiny in our future work for FEMA in the shocktube once we have an operating thermal source.

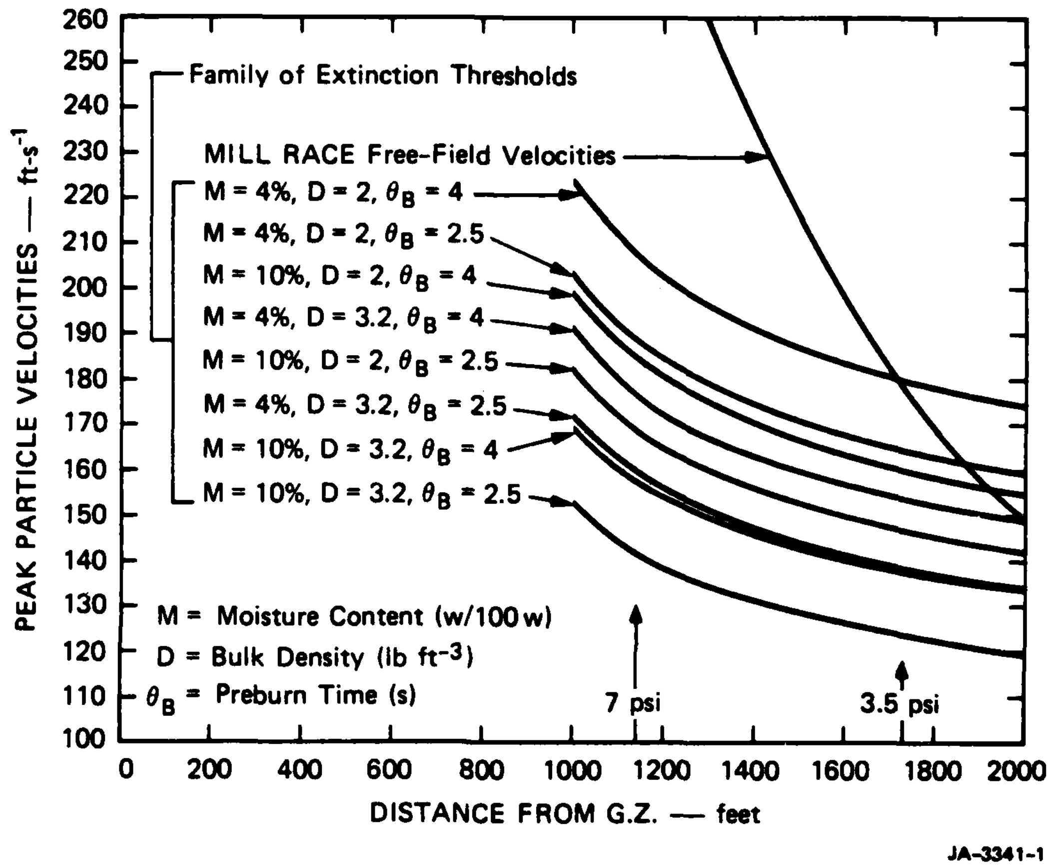

FIGURE 16 PREDICTED EXTINCTION THRESHOLDS FOR MILL RACE PARTICLE VELOCITIES COMPARED WITH FREE-FIELD CONDITIONS

V CONCLUSIONS AND RECOMMENDATIONS

In the absence of flow-stagnating geometries and environmental configurations (such as rooms), flames are readily swept off burning surfaces. This is observed at very low overpressures, and/or correspondingly low air velocities. Whether the fire is then permanently extinguished depends upon factors that permit reestablishment of flames at the volatile fuel source. These factors are of two kinds: the fuel's requirement for heat feedback to maintain volatile flow, and the fuel's ability to form surface char and retain heat. Class A fuels typically require substantial heat feedback to maintain their supply of the volatile thermal-decomposition products needed to sustain flames, and they often form chars that can support glowing or smoldering combustion, serving as a localized heat source to reestablish flames under suitable conditions. In contrast, Class B (i.e., liquid) fuels commonly require little, if any, heat feedback to vaporize (though there are numerous exceptions) and they never form chars.

The permanent extinction of combustion is observed only at significantly higher overpressures (and/or free-stream air velocities) than required to displace flames from the fuel supply. How much higher depends upon (1) how far the flame is displaced before it can return through the wake of unburned vapors that are swept from the fuel source by the airblast after the flames were removed, (2) the properties of the fuel/air wake through which the flame must return, especially the composition of, and turbulence in, that wake, and (3) how long the fire has burned before airblast arrival. (Especially in charring fuels, but this could apply to noncharring fuels as well.) **Concerning these three factors that determine the tenacity for fire to reestablish itself:**

- Factor (1) is related to air particle displacement behind the shock, which depends, in turn, on the rate of overpressure decay, and is represented (at fixed value of peak overpressure) by the positive phase duration (t_+).

- Factor (2) is determined by certain fundamental properties of the fuel source (which have yet to be unambiguously determined), complex flame-holding characteristics of its cross section in the direction of air flow, and turbulence-intensifying diffractional effects on the shock due to the density irregularities in the flame envelope during shock propagation.
- Factor (3), the preburn time, is a function of weapon yield and height of burst (in situations of primary fires interacted upon by the airblast from the same explosion that caused the fires).

Our plan of work for the research of Federal Fiscal Year 1981 (reproduced as Appendix A) was to have included a systematic investigation of the dependence of extinction-threshold overpressures in representative examples of charring and noncharring fuels on the characteristics of nuclear airblast (notably positive phase durations and delays in airblast arrival). Its execution in full was unfortunately thwarted by impediments beyond our control. This systematic investigation of the two principal airblast variables associated with variations in conditions of nuclear explosions--and already shown to have a strong influence on airblast extinction of fire--remains a high priority activity of the FEMA-funded study of air/blast interactions. Completion of the necessary facility modifications, planned as a part of the current contract, is urgently recommended for FY 82 or as soon thereafter as funds can be made available.

Beyond such requirements for data directly applicable to forecasting fire effects of nuclear explosions in a few representative classes of practical urban materials, the longer term goal (of interest to both DNA and FEMA) is a reliable and generally applicable methodology for damage/threat prediction. Complications due to geometry will need experimental investigation, scaling rules will need to be developed and verified. Some progress has already been achieved.

Previous limited experiments in the blast/fire facility showed strong and complicated effects of nonflat and other airflow-perturbing geometries on fire behavior. Present tests on common liquid fuels representing various combinations of physico-chemical properties demonstrate the strong and as yet unpredictable effects of fuel type.

These observations point to the limited practical applicability of a simple flame-displacement mechanism as a basis for theoretical development. These results affirm the need for a fundamental understanding of the fluid dynamics of compressible/transient fluid flow interactions with diffusional/unsteady combustion processes.

Results of last year's experiments with wood cribs ignited with alcohol had already shown that the strength of the airblast needed to blow flames out depends strongly on the preburn time, i.e., on the delay between ignition and application of airblast, and generally on the thermal state of the fuel at airblast arrival. Present tests on cribs made up of thinner elements confirm the role of preburn time, and the results are instrumental to develop and test scaling rules for preburn time. The application of such scaling rules to even finer materials--which are more readily ignited by the nuclear thermal pulse--requires further verification.

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Appendix A

WORK PLAN

EXPERIMENTAL EXTINGUISHMENT BY BLAST

INTERIM WORK PLAN

This work plan contains Tasks 1 and 2 of the proposal (corresponding to Parts B and A, respectively, of the Statement of Work). In the proposal, that experimental work in Task 2 which was intended to be done using the thermal radiation source (CARRS,* designed by SAI) was included conditionally, pending the delivery of complete design, the successful assembly and incorporation in the shocktube, and satisfactory in situ operation of the prototype (i.e., successful execution of Task 1). As the complete design and component parts to be supplied by SAI have not been delivered, the completion of Task 1 will likely not occur in time to use it extensively in experiments in Task 2. Therefore, the work plan is structured as follows. Tasks 1 and 2 will be conducted independently. Substitute ignition methods will be used in Task 2, including tests which are preparatory for the MILL RACE field test. (Completion of Task 1 in time to conduct the pre-MILL RACE series of tests is not expected even if delivery of CARRS design and parts occurred presently.) When the CARRS has been brought to satisfactory operation in situ in the shocktube facility according to the standards described in the proposal, this Work Plan will be superceded by a revised Work Plan reflecting any modification of Task 2 to include use of CARRS in shocktube experiments.

Whereas the proposed approach had envisioned extensive experimentation with representative urban fuels, such (class A) fuels cannot be gainfully tested without a proper radiant-ignition simulation such as promised by CARRS. Therefore, the majority of such tests will await the successful operation of CARRS. Nevertheless, a limited number of class A tests may be included in several topics explored in Task 2 (such as airblast characteristics).

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*Carbon Rod Radiant Source

Task 1: Thermal Source Installation and Checkout

In order to provide for simulation of fire initiating/extinguishing effects of airblast and thermal radiation interactions of nuclear explosions, a suitably designed thermal radiation source is required for use with the shocktube. SRI shall complete the fabrication of a multimodule, electrically heated graphite-strip thermal radiation source (CARRS) designed and tested in prototype by SAI under contract to FEMA, and install and proof test this radiation source in the SRI operated blast/fire shocktube facility at Camp Parks, California. Specific work and services shall include the following:

1. Procure the necessary materials, supplies and components as specified by the SAI design. Specifically excluded is the prefabricated reflector array that is to be supplied by SAI at no cost to SRI.
2. Modify the existing test section and experimental work-area enclosure of the facility at Camp Parks to accommodate the thermal radiation source and its components, including a large chemical-cell storage-battery power supply with recharging capabilities (henceforth called CARRS).
3. Fabricate and install the CARRS system according to design specifications and instructions provided by SAI.
4. Operate the system and employ radiant flux/fluence diagnostics to test its performance. System performance will be compared to the following design goals:
    a. Peak flux--conveniently adjustable in 30% increments up to at least 15 cal cm^{-2} sec^{-1}.
    b. Minimum pulse rise time--1 to 2 seconds at maximum electrical power dissipation.
    c. Exposure area--1/3 m^2 (horizontal plane near midplane of shocktube) uniform to $\pm$ 20% of average flux.
    d. Repeatability--less than 20% variation in either peak flux or fluence between replicate runs (90% confidence).
5. Ascertain system limitations in simulating ignition of materials by nuclear thermal pulses. Performance will be judged on:
    a. Range of peak-flux/fluence ratios.
    b. Perturbing influences of emitted flame and/or smoke or pulse characteristics.
    c. Extraneous interferences of the system with fire/blast behavior.
    d. Frequency and difficulty of repair and maintenance.

Task 2: MILL RACE Pre-Event Testing and Development of Scaling Rules

Subtask 2a: MILL RACE Pre-Event Testing

Since the thermal pulse simulator (CARRS) is not available to select suitable debris mix for MILL RACE fire experiments and calibrate their ignition response, two compromise methods are resorted to. Debris (fuel bed) properties will be selected based on available thermal ignition criteria (from well correlated past theoretical and laboratory test data) and on limited trial runs with TRS at Kirtland AFB. The material planned for use at MILL RACE is shredded (¼" wide strips) pure cellulose filter paper of thickness(es) tailored for ignition at various selected stations and in several orientations in the MILL RACE tests. A candidate thickness is 22 mil for the filter paper elements, although other candidate thicknesses in the 10-50 mil range will be considered and may be tested in the shocktube.

Ideally, if the thermal flux and fluence were known for the candidate SRI stations at MILL RACE and if the flux and fluence spacial distribution were known at the pre-MILL RACE TRS tests, the appropriate stations and the corresponding fuel properties could be chosen for the MILL RACE event and verified at the TRS tests. However, the radiation distribution near the TRS will not be known accurately prior to MILL RACE or the TRS tests and this precludes the accurate and unambiguous knowledge of the debris ignition response.

With these uncertainties in mind, shocktube experiments will attempt both to choose the debris properties suitable for extinction threshold bracketing at MILL RACE and gain some knowledge of the sensitivity of the extinction response of the candidate materials near the ignition/blast conditions at MILL RACE. Such sensitivity check should indicate that extinction threshold bracketing at MILL RACE is likely even should the actual ignition and blast conditions at MILL RACE differ to some degree from the specifications given us..

Assuming the specified blast conditions (3.5 and 7 psi) at the stations planned for debris fires are met, the thresholds of the designed debris fires, as tested in the shocktube, should fall near the mid-point of this range so that we obtain the greatest amount of information. Although the range of fire conditions with great extinction-threshold sensitivity

(potentially caused by ignition conditions or by the thermal-response properties of the fuel beds, such as thermal thickness) is generally of great interest, if either the 3.5 or the 7 psi threshold falls into such a highly sensitive range the results could be inconclusive if extinction or lack thereof occurs at both stations.

The fuel bed ignition in the shocktube tests will be done using a near-horizontal flat propane flame spanning the top fuel bed surface (a 2' x 10" rectangular area). The top (1-3) layers of the debris volume will be ignited, with shock arriving at the end of the ignition phase, i.e., a predetermined (short) time after ignitor cut-off. Short-overpressure-duration blast will be used and generated by pressurization of the short driver section. Although the blast thus obtained will be shorter (between 70 and 133 ms for shocks of 2-8.9 psi) than the positive phase duration specified for MILL RACE (in the range of 200 to 380 ms), the extra effort needed to obtain comparable blast durations is not warranted by the intent, which is to designate the correct blast/fire conditions to be tested effectively at MILL RACE. For correspondence with MILL RACE fuel bed mounting, pans will be tested with fuel pan base at grade (sitting on test stand) as well as with top debris surface and pan lip at grade (pan is submerged within test stand with the top surface flush with test stand top surface).

Subtask 2b: Development of Scaling Rules

A balanced plan has been prepared for this subtask, in which the experimental capability of the shocktube is steadily increased and new types of problems are addressed as well as outstanding problems are attacked in hope of settling questions raised in past work. Recommendations of the second annual report (December 1980) of Work Unit 2564A are partially incorporated into the planned work. Work under subtask 2b falls into the following four topic categories:

A. Airblast Characteristics

B. Fuel Properties

C. Target Configuration

   1. Airblast perturbation/degradation by obstacles.
   2. Angle of incidence of blast with respect to target fire.

D. Scale Effects

A. Airblast Characteristics

In this year's plan, the focus in investigating airblast characteristics is on the duration of airblast positive phase. Strong extinction action of long-duration airblast (3-4 sec) was noted in 1979 tests, when 3-foot hexane fires were blown out with overpressures down to the 1 psi level. In contrast, in the 1980 tests with short duration airblast ($\sim$ 70 to 133 milliseconds), the hexane fires showed a markedly higher resistance to airblast, with extinction threshold for the 3-foot beds being near 5.1 psi. It appears, therefore, that positive phase duration plays an important role. The plan is to investigate and quantify this dependence by using intermediate positive phase durations. A series of tests will be made for a fuel (class B) or--if time and funds permit--two fuels (class B and class A).

Moderate modification of the shocktube system is required to obtain intermediate airblast durations. Presently, the pressure plenum can be vented incrementally through its upstream orifice to obtain reduction of the maximum (no-venting) duration of the positive phase, i.e., obtain some range in the longer durations. However, to obtain greater testing turnaround time and improve efficiency of the procedure alterations are desirable. The candidate modifications include a different venting release mechanism at the plenum upstream end or an air-volume retentive method of augmenting the plenum volume (i.e., reduce the effective releasable-air volume of the plenum). On the other hand, the short duration pulses now obtainable by pressurizing only the short tube driver section can be extended by extending the length of the tube driver section (in the upstream direction). The most suitable method of obtaining intermediate airblast durations will be chosen, with capital and testing costs both considered as well as the technical merit of the chosen method in expanding the shocktube flexibility and capabilities.

B. Fuel Properties

Similar gap exists in our ability to quantify how fuels, in general, respond to airblast. At the two extremes lie hexane data and methanol data. The former easily resists extinction up to the 5 psi level (flush

fuel bed with shock at zero incidence angle), while the former was extinguished even at 1.1 psi (both with short-duration airblast). Several questions arise. Are the extinction thresholds of various common liquid hydrocarbons--perhaps industrially the most widely used flammable liquids--similar enough to hexane data that hexane can be used as a model hydrocarbon in most blast extinction problems? What other common fuels are as easily extinguishable as methanol, posing a significantly lesser danger of fire persistence after blast than similar hydrocarbon fuels? In addition, data on liquid fuels whose fires are of intermediate resistance to blast relative to the known extremes of hexane and methanol are needed so that parallel analytical efforts are aided by a greater range of data. Several class-B fuels will be tested to answer the above questions.

C. Target Configuration

1. Airblast Perturbation/Degradation by Obstacles

Effects of this nature have been identified and received initial study in last year's work. It was observed that even with small (1 3/4" high) barriers upstream of the fuel bed the extinction overpressure thresholds increased. However, the full potential of this effect has not been explored yet to identify hard-to-put-out target (fuel-bed and surroundings) configurations. Moreover, scaling rules for the barrier effects have not been established. Their action during intermediate and long-duration airblast is similarly unexplored; all tests with barriers have used short duration airblast only.

Experiments are planned to obtain further understanding and quantification of the effect of obstacles and airblast extinction through their airblast-perturbing and flame-holding action. Tests will involve fuel-bed scale and barrier geometry and placement variation to look for scaling rules governing extinction. The effect of longer airblast duration will be explored, if time and funds permit, to see if the eddy-reignition mechanism is effective over longer durations or if it is transient in nature and thus favors only the short-duration airblast conditions. Class B fuels are suitable candidates for this work, but class A fuels will be considered if feasible.

2. Angle of Incidence of Blast with Respect to Target Fire

The direction of shock travel in the shocktube is, of course, fixed and takes place along the axis of the shocktube. The angles of airblast incidence

relative to the target fire which are of interest in relation to nuclear thermal pulse ignition are such that the target (fuel bed surface) be visible from the airblast incidence direction (i.e., ground zero) with the nuclear fireball located at some height above ground zero. (In this way even horizontal fuel beds are ignitable even though the airblast wave may have zero incidence angle, i.e., be perpendicular, with respect to the fuel bed.) Such target orientations can be represented by fuel bed rotation (hypothetically up to 90^{o}) about the upstream fuel bed edge and a rotation (up to 90^{o}) about either side edge with a pivot about a fixed upstream corner of the bed to permit a view angle by a hypothetical fireball upstream. The former represents frontal incidence with progressive elevation of the downstream fuel bed edge until at 90^{o} the fuel bed is vertical, with head-on shock incidence. The latter rotation yields and inclined almost-side-on incidence. Due to shocktube cross section limitations, only moderate-scale fires at small ($< 30^{o}$) angles can be tested.

D. Effects of Fire Scale on Airblast Extinction

One consequence of increase of scale of turbulent pool fires is the increase of radiant feedback (per unit area) to the fuel bed with increasing optical flame depth. The increasing radiant feedback increases the fuel pyrolysis rate (per unit area), until the fuel pyrolysis rate levels off when the flames above the fuel bed appear, to a receiving unit area of the fuel surface, as a blackbody at the flame radiation temperature (i.e., the flame has become optically thick).

This effect of increasing pyrolysis rate with scale may be studied by providing flame radiation augmentation by externally supplied radiant flux. It may be feasible to significantly increase the burning intensity by placement of two radiant panels along the test stand and fuel bed (positioned externally to the shocktube when the breach is closed). Both class A and class B fuels can be tested wit this method, although class B fuels are experimentally far simpler in this method.

This approach has a complementary nature to a task proposed for DNA work studying the effects of (gas) fuel supply rate. The experiments described here would await till at least preliminary results are available from the DNA effort. These may also guide the ultimate test design and method for the non-gaseous fuels studied here.

Appendix B

SHOCKTUBE TESTS - DATA COMPILATION

Table B-1

CLASS B FUEL TESTS
Bed Length = 36 in.

Test No.	Fuel	Preburn Time	Mean Overpressure (psi)	Positive Phase Duration (ms)[a]	First Flashback (ms)[b]	Observation
1	Kerosene	15	5.59	135(57)	-	Fire out
2	Kerosene	15	2.06	108(61)	-	Fire out
3	Kerosene	15	0.91	107(61)	?	Fire sustained
4	Kerosene	15	1.49	109(61)	137	Fire sustained
5	n-Pentane	10	4.36	174(58)	-	Fire out
6	n-Pentane	5	2.42	175(60)	?	Fire sustained
8	n-Pentane	5	3.16	150(59)	-	Fire out
9	n-Pentane	5	2.80	159(57)	133	Fire sustained
10	n-Pentane	5	3.04	129(56)	-	Fire out
11	Acetone	15	3.60	74(59)	-	Fire out
12	Acetone	15	2.53	71(55)	-	Fire out
13	Acetone	15	1.94	70(62)	-	Fire out
14	Acetone	15	∿1.0	71(60)	?	Fire sustained
15	Acetone	15	1.43	70(61)	∿200	Fire sustained
32	n-Hexane	15	∿6.2	>150	-	Fire out
33	n-Hexane	15	∿4.0	>150	?	Fire sustained

[a]The increases in positive phase durations for kerosene, pentane, and hexane tests are caused by pressure increases due to fuel combustion during test. Numbers in parentheses represent the time over which pressure was averaged.

[b]Time measured from shock arrival at test section.

Table B-2

WOOD CRIB TESTS
3/8-in. Stick Cribs

Test No.	Crib Initial Weight (g)	Preburn Time (s)	Approx. Measured Wt. Loss (%)	Mean Overpressure (psi)	Observation
50	1788	111	(42.9)	6.92	Fire sustained
51	1569	107	(61.4)	5.91	Fire sustained
52	1559	88	(44.3)	6.88	Fire sustained
53	1683	88	(28.8)	5.88	Fire sustained
57	1698	60	15.3	4.57	Fire out
58	1731	60	15.1	3.05	Fire out
59	1755	60	12.8	2.02	Fire out
60	1783	60	15.7	1.24	Fire sustained
61	1740	73	19.3	2.21	Fire out
62	1878	72	17.3	1.69	Fire sustained
63*	1670	71	12.8	7.17	Fire out
64*	1669	91	(60.9)	6.75	Fire sustained
65*	1704	85	31.0	7.90	Fire sustained
66*	1708	70	14.1	7.92	Fire out
67*	1673	85	23.9	7.98	Fire out
68*	1693	85	25.1	9.88	Fire out
70*	1768	87	31.6	2.64	Fire sustained
71*	1780	62.5	13.1	2.56	Fire out
72*	1624	79	34.3	2.66	Fire sustained
73*	1706	72	21.1	2.60	Fire sustained
74*	1752	80	25.5	3.31	Fire sustained
75*	1750	86.5	33.0	4.10	Fire sustained (reignition)
79*	1742	69	18.2	9.05	Fire out
80*	1769	71	17.2	8.88	Fire out
81*	1781	78	25.0	8.77	Fire sustained (reignition)

*Crib center support stick was removed.

Table B-2 (Continued)

Test No.	Crib Initial Weight (g)	Preburn Time (s)	Approx. Measured Wt. Loss (%)	Mean Overpressure (psi)	Observation
39	1820	60[+]	7.7	2.16	Fire out
40	1741	60[+]	9.8	2.27	Fire out
41	1891	60[+]	9.0	1.11	Fire out
42	1900	90[+]	(46.6)	3.40	Fire sustained
43	1822	90[+]	27.0	5.77	Fire out
45	1842	90[+]	(32.1)	4.82	Fire sustained (reignition)
46	1843	105[+]	21.1	4.47	Fire out
47	1710	105[+]	35.7	4.89	Fire sustained
49	1745	105[+]	(60.0)	6.89	Fire sustained

[+] Slower burning cribs--unframed wick slowed down ignition

Table B-3

WOOD CRIB TESTS
3/4-in. Stick Cribs

Test No.	Crib Weight (g)	Preburn Time (s)	Measured Wt. Loss (%)	Mean Blast Over Pressure (psi)	Observation
76	3864	135	23.3	9.55	Fire sustained
77	3608	128.4	14.2	9.04	Fire out
78	3428	134	16.9	8.7	Fire sustained
82	3670	96	6.8	0.91	Fire sustained
83	3658	95.6	5.9	1.24	Fire out
84	3391	89.5	5.9	0.95	Fire out
85	3432	108	9.3	1.43	Fire sustained

Table B-4

DEBRIS FIRE TESTS

Test No.	Fuel/ Fuel Arrangement Type[a]	Burner-on Period (s)	Total Preburn Time (s)	Mean Over-Pressure (psi)	Observations: Fire Out?	Observations: Residual Smolder Present?	Observations: Did Fire Rekindle?
1A	Blotter paper/A	?	?	10.	Yes	Yes	No
2A	Blotter paper/A	14	14	10.	Yes	Yes	No
4A	Blotter paper/A	9.8	9.8	3.5	Yes	?	Yes, after 15 sec
5A	Blotter paper/A	9.5	9.5	3.5	Yes	-	No
6A	Blotter paper/A	30	30	2.	Yes	?	Yes, after 10 sec
7A	Blotter paper/B	7	9	7.	Yes	Minor	No
8A	Blotter paper/B	7	14.5	3.5	Yes	Yes	Yes, with blowing
9A	Blotter paper/B	7	15.7	7.	Yes	Localized	Yes, with blowing
10A	Filter paper/B	7	14.5	7.	Yes	Little	No
11A	Filter paper/B	7	14.5	3.5	Yes	Some	No
12A	Filter paper/B	7	14.4	1.75	No	Yes	Probably

[a]Fuel Arrangement Type A: 2 ft by 9 3/4 in. pan (2 1/2 in. deep)
Fuel Arrangement Type B: 6 in. by 10 in. tray (1 in. deep)

Appendix C

WOOD CRIB FREEBURN TESTS

WOOD CRIB FREEBURN TESTS

This appendix focuses on the relationship between the structural (geometrical) characteristics of wood cribs and the empirical description of wood crib burning. Specifically, the crib mass loss history and steady-state mass loss rate are discussed and the design of the scaled crib used in this year's shocktube tests is developed. This discussion supplements the discussion of crib burning developed previously by the authors and included in Ref. C-1.

A useful recent review of "Crib Fire Modeling" is contained in Ref. C-2 and the approach used here is an application of the concepts summarized therein. Ref. C-2 deals with square-base cribs, which rest on their bottom-most layer (there are no extra supports or elevation of crib). The cribs discussed here have rectangular base with crib length-to-width ratio of about 3.75 and 3/4-in. elevation of the bottom crib layer. Both structural differences have been verified by our experiments to have a negligible effect on the empirically derived, scaled steady weight loss rate. Moreover, previous discussion (Ref. C-1) and experiments show that because of the localized nature of crib burning controlling factors, the crib base areas are essentially additive: it was observed (and is supported by literature) that a crib of length-to-width ratio of 3 has the same weight loss rate (within experimental accuracy) as 3 square-base cribs burning independently. Therefore, the concepts of Ref. C-2 are used essentially without modification and their application is below.

It has been established that, in general, the steady burning (weight loss) rate in a wood crib can be correlated with the parameter $\sqrt{sb}\, A_v/A_s$ as follows:

$$\frac{\sqrt{b}\,\frac{dm}{dt}}{A_s} = \frac{K A_v \sqrt{sb}}{A_s} \qquad \text{C-1}$$

$\frac{dm}{dt}$	weight (mass) loss rate
b	stick dimension (width)
s	spacing between sticks in a layer
A_v	total cross-sectional area of the vertical vents in the crib volume
A_s	total surface area of the exposed wood in crib
K	constant of proportionality (includes fuel type effects, moisture effects, etc.)

In a loosely packed crib the left side of Eq. C-1 becomes independent of the parameter $A_v\sqrt{sb}/A_s$ and the crib weight loss rate therefore becomes merely proportional to the total fuel surface area A_s and is inversely proportional to the square-root of the stick thickness, or

$$\frac{dm}{dt} = KA_s/\sqrt{b} \qquad \text{C-2}$$

Figure C-1, a reinterpretation in Ref. C-2 of the data of Block (Ref. C-3) shows graphically the empirical basis of equation C-1. The data represent crib fires corresponding to various crib porosities.

Figure C-2 presents a similar reinterpretation of Block's data by Heskestad (Ref. C-4); the curve is said to represent all data points within $\pm$ 20%, as accurately as does Blocks' own correlation. However, the averaged assymptote appears to correspond to a lower value of K than Table C-1 and Fig. C-1 suggest, being lower than 1 $mg/cm^{1.5}s$.

Ponderosa pine was used in the majority of Block's tests. The values of K found by Block for the various species of wood are reproduced in Table C-1. Block measured the dependence of K on the moisture content,* he recommends the value $K = 1.05 \times 10^{-3} g/cm^{1.5}s$ for moisture content between 5-10%.

*For Ponderosa Pine, the variation of $K[g/(sec\ cm^{1.5})]$ with moisture content M(%) was found to be $K = (1.2 \times 10^{-3}) - (2.2 \times 10^{-5})M$.

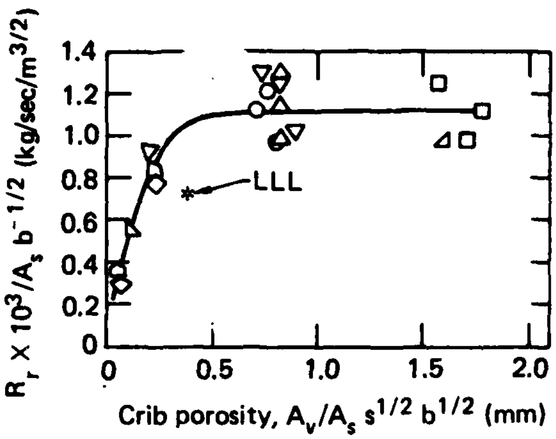


FIGURE C-1 SIMPLIFIED CORRELATION FOR BLOCK'S DATA ON UNCONFINED BURNING RATES OF WOOD CRIBS (REF. 2)

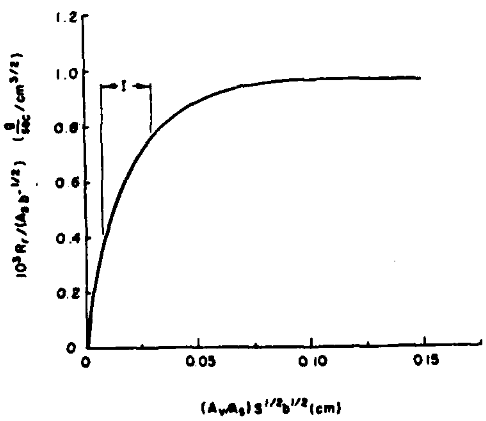


FIGURE C-2 SIMPLIFIED CORRELATION FOR BLOCK'S DATA ON UNCONFINED BURNING RATES OF WOOD CRIBS (REF. 4)

Table C-1

VALUES OF K FOR VARIOUS SPECIES OF WOOD

	K, mg/(sec $cm^{1.5}$)	ρ(dry), g/cm^3	M %
Ponderosa pine	1.03	0.500	7.9
Ponderosa pine	1.07	0.345	7.7
Birch	1.30	0.630	7.3
Idaho pine	0.87	0.405	8.1
Maple	1.33	0.555	7.6
Oak	1.33	0.700	6.8
Redwood	0.86	0.335	7.7
Sugar pine	0.88	0.330	7.3
Western hemlock	0.96	0.565	7.6
Whitewood	1.11	0.425	6.9

During the 1980 crib freeburn tests (Ref. C-1), the steady (maximum) burning rate of the 3/4-in. stick cribs was found to be, on the average, 9.0 g/s. With the total fuel surface area of the 3/4-in. stick cribs calculated as 11,918 cm^2, the specific (per unit fuel surface area) steady burning rate is 0.755 mg/s cm^2. This yields the value for constant K of 1.04 mg/s $cm^{1.5}$. During this year's tests with 3/8-in. stick cribs, the corresponding values were 14.2 g/s steady burning rate and 1.085 mg/s cm^2 specific burning rate. (The total surface area of the 3/8-in. stick cribs was 13,091 cm^2, only slightly higher than that of the 3/4-in. stick cribs.) The constant K is 1.06 mg/s $cm^{1.5}$ for the 3/8-in. stick cribs.

These values are in very good agreement with those found by Block (Table C-1). They lie between the values given for Ponderosa pine at two densities. Kiln-dried pine shelving was used for our cribs in both years. We measured the density of the wood used this year: for wood with less sap (favored) the density was 0.40 g/cm^3, and for the more sappy wood the density was 0.52 g/cm^3. Because the less sappy wood was favored, the density of the cribs was probably closer to the lower value. From Block's table (Table C-1) the value of K for the crib density between 0.40 and 0.45 g/cm^3 would be 1.05 mg/s $cm^{1.5}$. This value, which lies between the values 1.04 and 1.06 measured here for the two crib types, is well supported by our experiments.

In the following two figures, the recorded burning histories of the two crib types are compared. Figure C-3 shows the specific weight loss versus time for two typical freeburn tests. The accelerated weight loss and earlier burnout of the 3/8-in. stick cribs is apparent. The constant (maximum) slopes, corresponding to specific weight loss rates of the cribs, are proportional to the square root of the stick thickness, as can be seen in Fig. C-4. In Fig. C-4 the abscissa is scaled by $b^{1/2}$ and the slopes of the two curves are therefore equal to the constant K (1.05 mg/s $cm^{1.5}$).

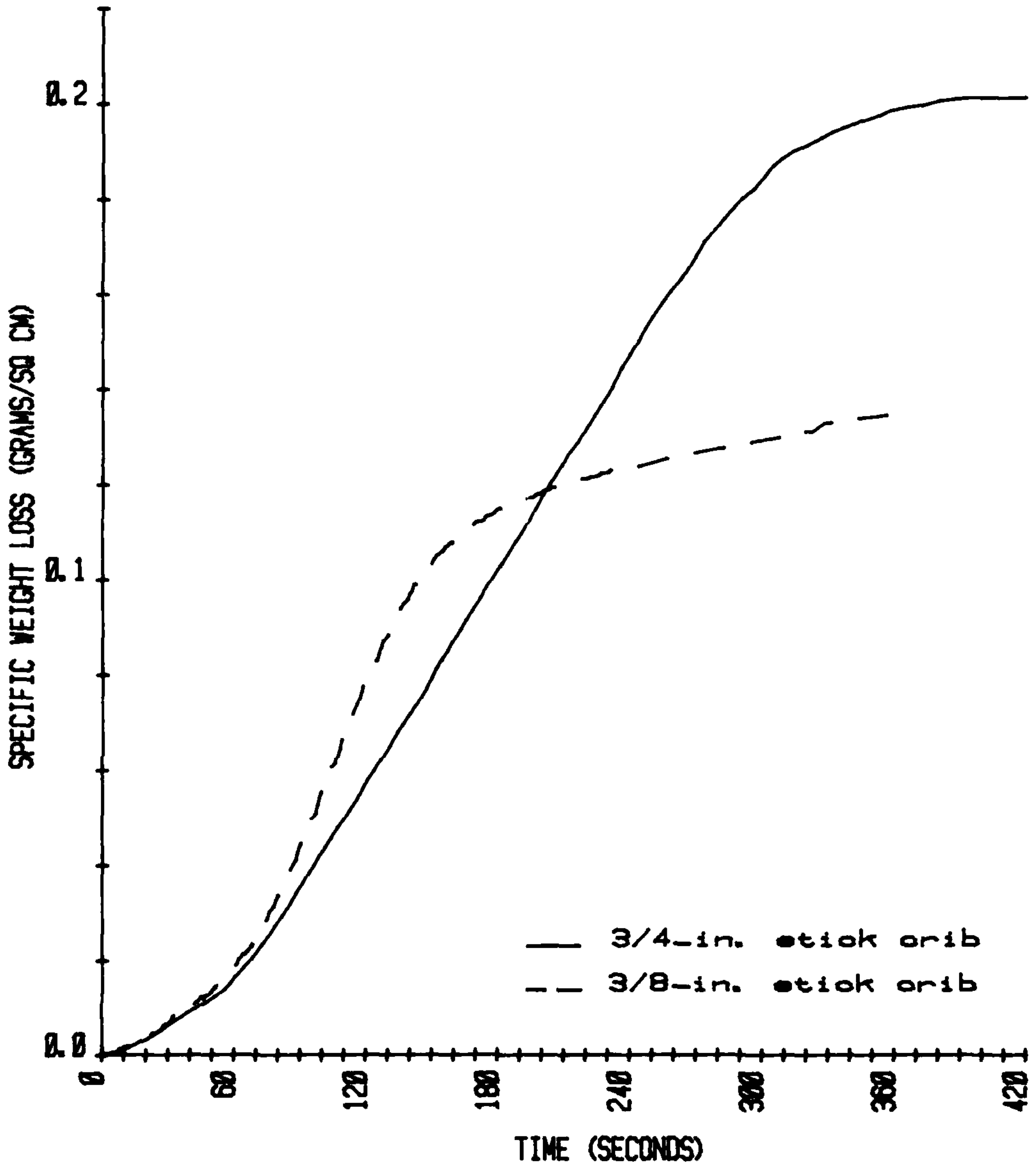


FIGURE C-3 SPECIFIC WEIGHT LOSS HISTORIES FOR 3/4-in. AND 3/8-in. STICK CRIBS (INCLUDES 1980 DATA FROM REF.1)

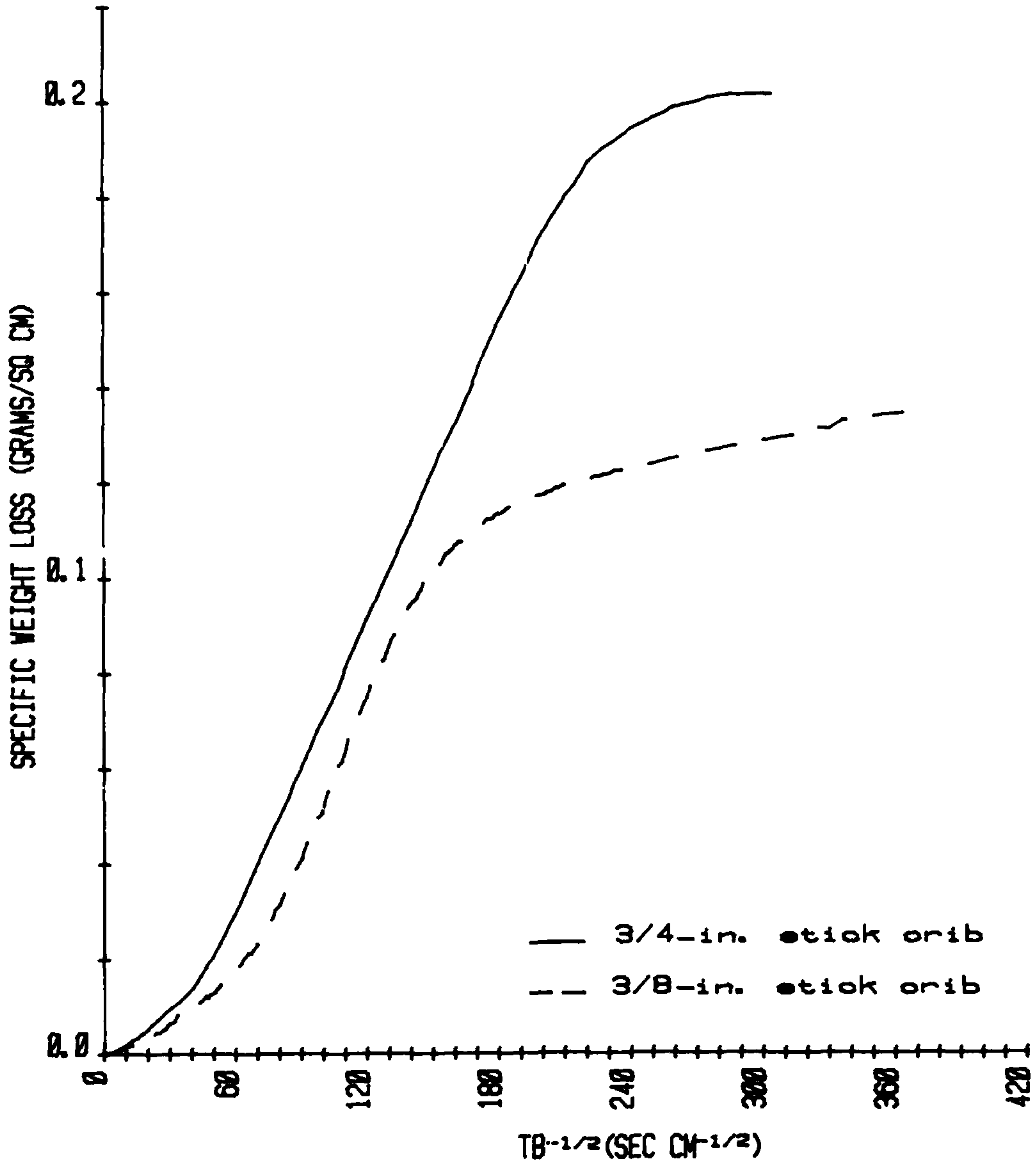


FIGURE C-4 SPECIFIC WEIGHT LOSS HISTORIES FOR 3/4-in. AND 3/8-in. STICK CRIBS, SCALED BY SQUARE ROOT OF STICK THICKNESS (INCLUDES 1980 DATA FROM REF.1)

REFERENCES

C-1. J. Backovsky, S. B. Martin, R. McKee, "Blast Effects on Fires," Final Report Under Contract DCPA01-79-C-0245, FEMA Work Unit 2564A, SRI International (December 1980).

C-2. N. Alvares, D. Beason, V. Bergman, J. Creighton, H. Ford, and A. Lipska, "Fire Protection Countermeasures for Containment Ventilation System" (Appendix E--Crib Fire Modeling, by J. Creighton) UCID18781, Lawrence Livermore Laboratory, 1980.

C-3. J. A. Block, "A Theoretical and Experimental Study of Non-Propagating Free-Burning Fires," XIII. Symposium (International) on Combustion, The Combustion Institute, p. 971 (1971).

C-4. G. Heskestad, "Modeling of Enclosure Fires," XIV Symposium International on Combustion, The Combustion Institute, p. 1021 (1973).

Appendix D

DIAGNOSTIC AND OTHER TESTS

DIAGNOSTIC AND OTHER TESTS

Diagnostic tests were conducted on shocktube instrumentation and its layout to optimize output signal of overpressure signatures; to check the blast overpressure field in and near the test section, to ascertain the blast properties at blast incidence on test fires; and to measure the effect of a test fire on the blast wave properties.

Blast Overpressure Signal Optimization

The test data evaluation indicated that because of an impedance mismatch between the pressure transducer and associated recording equipment, an underdamped condition existed. The underdamped condition caused ringing in the circuitry, producing erroneous signal fluctuations. Apparent pressure excursions resulted, with both higher and lower-than-actual values.

A Voltage Controled Oscillator (VCO) and associated discriminators operating in the 180 KHZ to 780 KHZ frequency range were used for each pressure to overcome the impedance mismatch problem. The usage of the VCO and discriminator equipment substantially increased the frequency response of the system. Because of the increased frequency response of the measuring system and because the pressure gage was not mechanically isolated or decoupled from the shocktube wall, the diaphragm rupture generated a high frequency ringing on the pressure gage signals. The use of an RC filter, which cut off frequencies above 1 KHZ, minimized the high frequency ringing superimposed on the pressure signal. Figure D-1 shows the effects of correcting the underdamped condition and the use of the RC filter. Although the initial rise time of the pressure pulse suffers a little in the "filtered" mode, the overall signal appears to be a more representative and accurate pressure time pulse. (The "filtered" case in Fig. D-1 includes use of VCO, discriminators, and the RC filter.) It appears desirable to include these modifications in the shocktube instrumentation system.

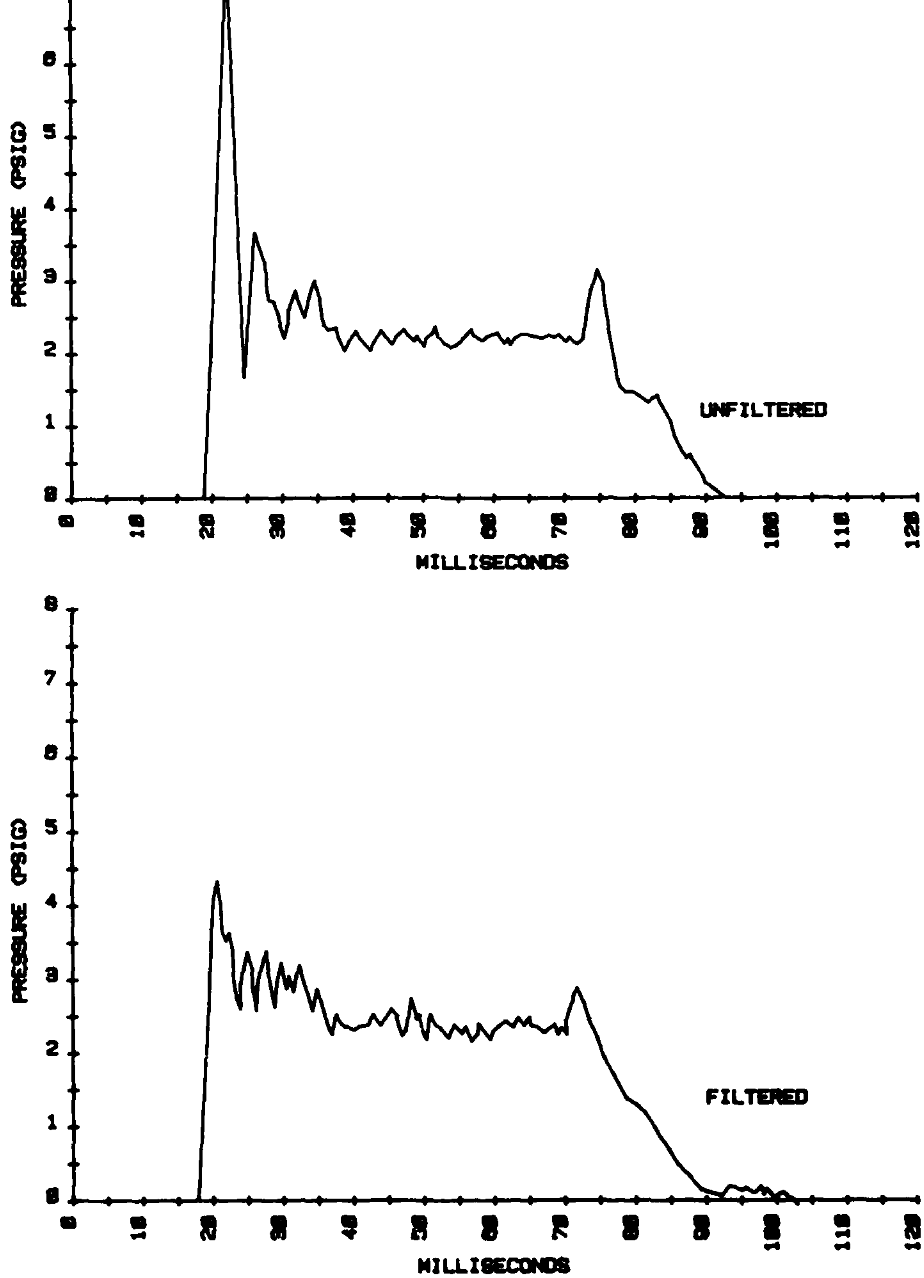


FIGURE D-1 PRESSURE PULSE RECORDED WITH THE SAME PROBE, ALONE AND WITH FILTER SYSTEM

With the signal improved, the actual pulse shape produced becomes more readily apparent. For the short-duration pulses produced by pressurizing only the upstream 30-foot section of the tube (between the diaphragm and the main pressure plenum), a flat-topped profile is expected. Figure 6 in Section II shows typical pressure pulses used during the year's testing; an almost ideal flat-topped profile is obtained. The flat-topped profile is not intended to duplicate the classical pulse shape of nuclear explosions--which would be obtained by use of the main pressure plenum--but serves as a useful research tool enabling study of fire response to blast with simple, step pressure jump (well-defined, constant overpressure).

Overpressure Field Measurements with and without Fires

Additional pressure measurements were taken in and around the test section to determine the effect of the test stand configuration on the overpressure. Figure D-2 schematically shows the location of the additional pressure gages. A small fuel bed 5 3/4 in. by 9 3/4 in. with M board substrates was mounted in the test stand along with gages P6 and P7. Pressure gage P5, mounted in a probe, measured side-on pressures. The probe was mounted upstream of the test section at the centerline of the tube. The P5 gage, mounted in the probe, was located ~ 11 in. upstream from the test stand.

The pressure measurements taken on the test stand, gages P6 and P7, indicate that the mean overpressure is fairly uniform upstream and downstream of the fuel bed in a no fire condition.* In tests conducted with a fire, gages P6 and P7 agree quite well for the first 20 ms, as shown in Fig. D-3. However, after 20 ms, gage P7 shows a marked increase in pressure. This could be attributed to an increase in fluid density downstream of the fuel bed caused by a mixture of unburned fuel vapors (hexane in this instance), and air. Gage P6 in this particular test shows a tendency to tail off, which may be due in part to pressure equalization

*Because of the low overpressures used the pressure pulses are less-than-ideal flat top profiles.

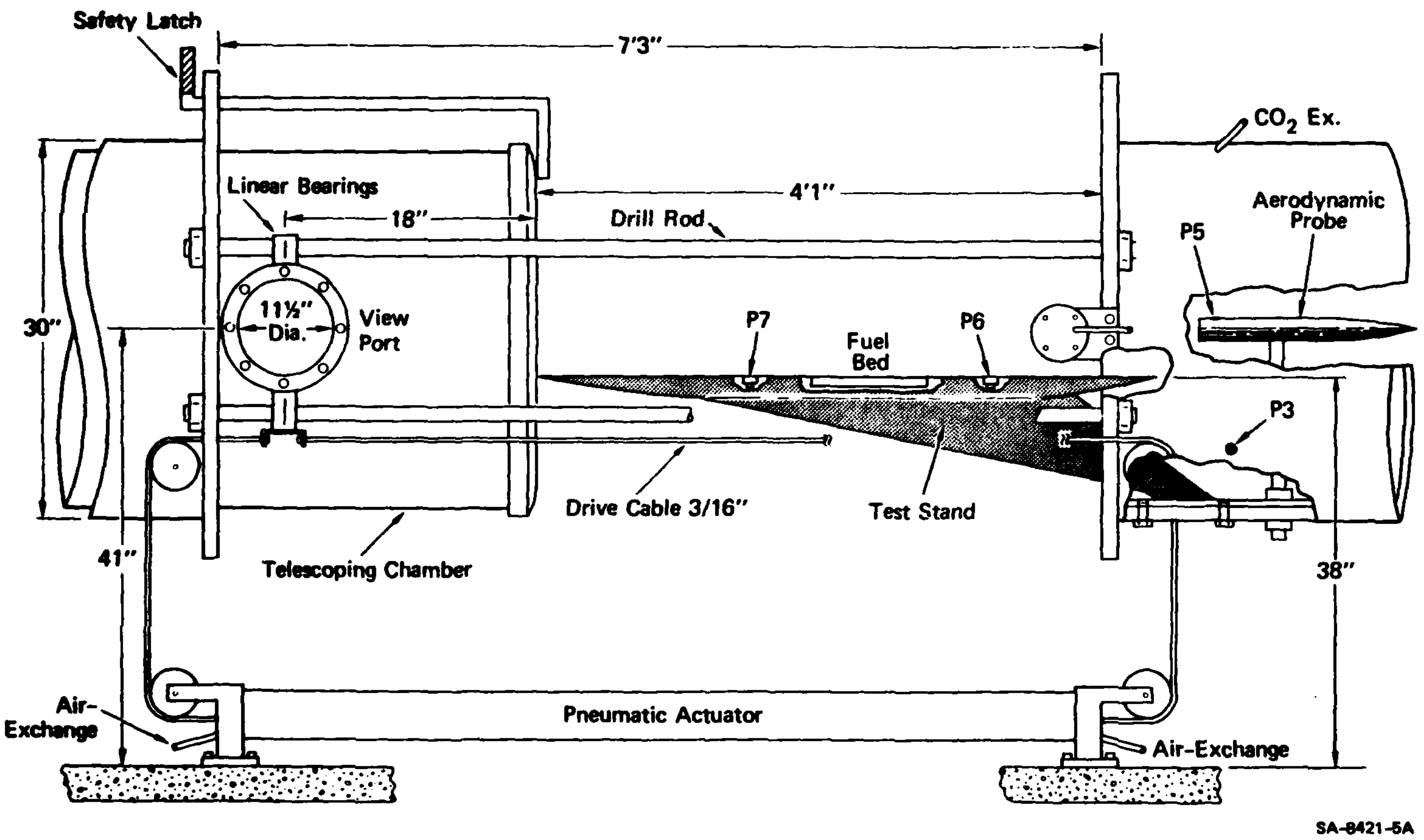


FIGURE D-2 SHOCKTUBE TEST SECTION WITH DIAGNOSTIC PRESSURE PROBES (P) SHOWN

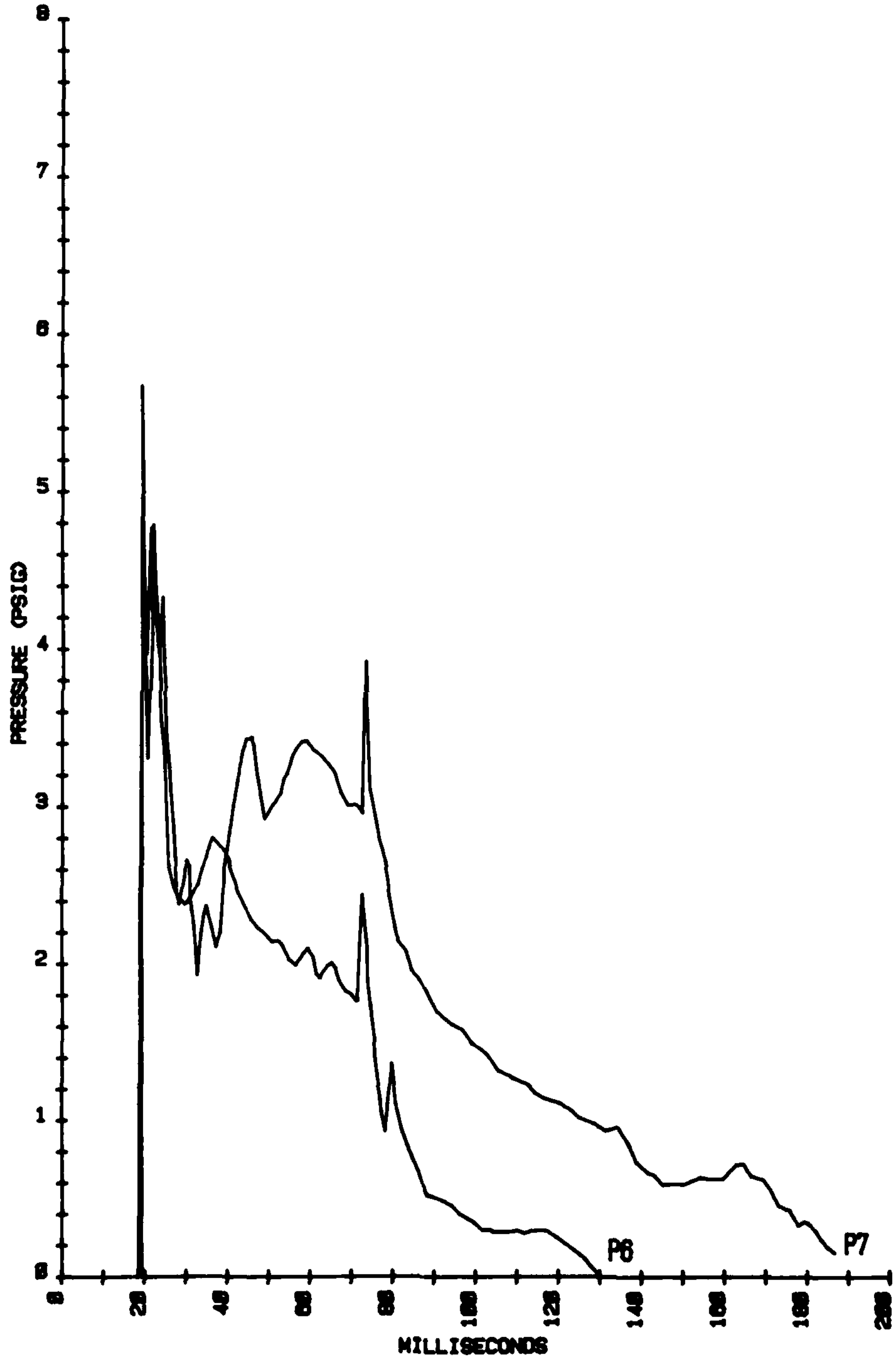


FIGURE D-3 PRESSURE PULSES RECORDED UPSTREAM (P6) AND DOWNSTREAM (P7) OF A SMALL TEST FIRE

within the test stand; however, since the test stand is not compartmentalized P7 should then show reduced overpressure level also, which it does not.

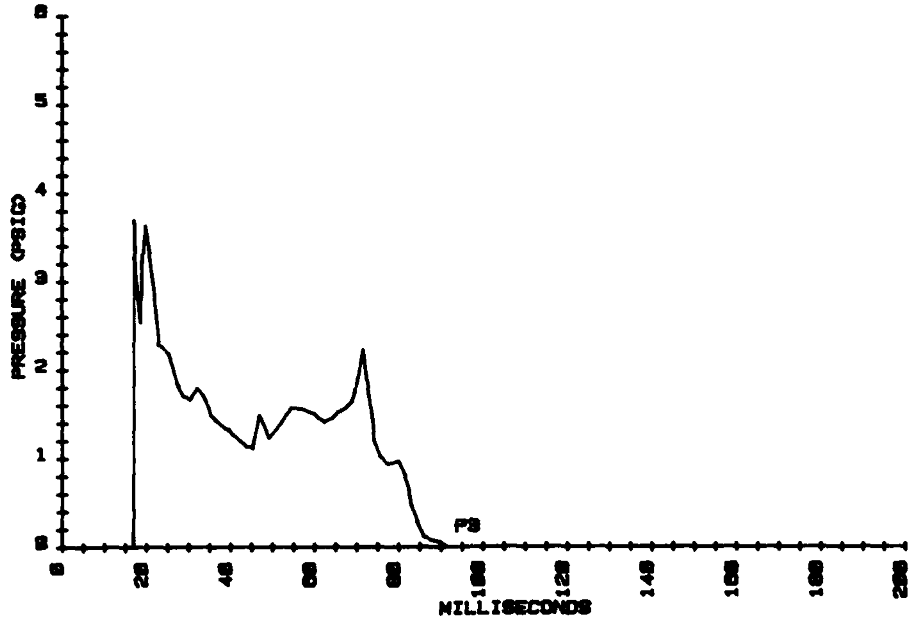
The pressure measurements from gages P3, P5, and P6 were compared to determine the uniformity of the mean overpressures a short distance upstream of the test stand and at the test stand itself. Figure D-4 shows that the pressures measured in the center of the driven tube (P5) and at the side wall of the tube (P3) agree quite well. However, if we compare, in another test, the side wall (P3) and the test stand (P6) measurements, Fig. D-5 clearly shows a reduction of the pressure of $\approx$ 45%. The reason for this pressure reduction is not clear at this point, but the uncertainty indicates that further diagnostic tests are needed.

Driver Gas Temperature

At the contact surface between the driven and driving gas, continuity requies that the pressure and particle velocity be the same on both sides, but not necessarily the temperature and density. If both the driven and driving gas are initially at the same temperature, then we know that the driving gas at the contact surface will be cold, having been isentropically expanded, and the driven gas will be hot because it has been shocked.

In a rigorously accurate simulation of a blast wave, we would heat the driving gas to a temperature such that when it had expanded to the shock pressure, it would have the same temperature as the shocked air ahead of it. (The alternative is to use a gas of lower (average) molecular weight.) This feature was included in the original design of the SRI Blast Simulator, but so far has not been produced because of lack of funds.

A question that should be explored is: what difference does the cold gas driver make as far as fire extinction is concerned? This question can be subdivided into qucstions as to the effect of the higher density of the cold gas on the flow, the effect of the cold gas on fuel enthalpy, and possibly others. The importance of the cold gas driver in fire extinction depends on overpressure and positive-phase duration at low overpressures; the contact surface between shocked and cold gas arrives much later than for higher overpressures.



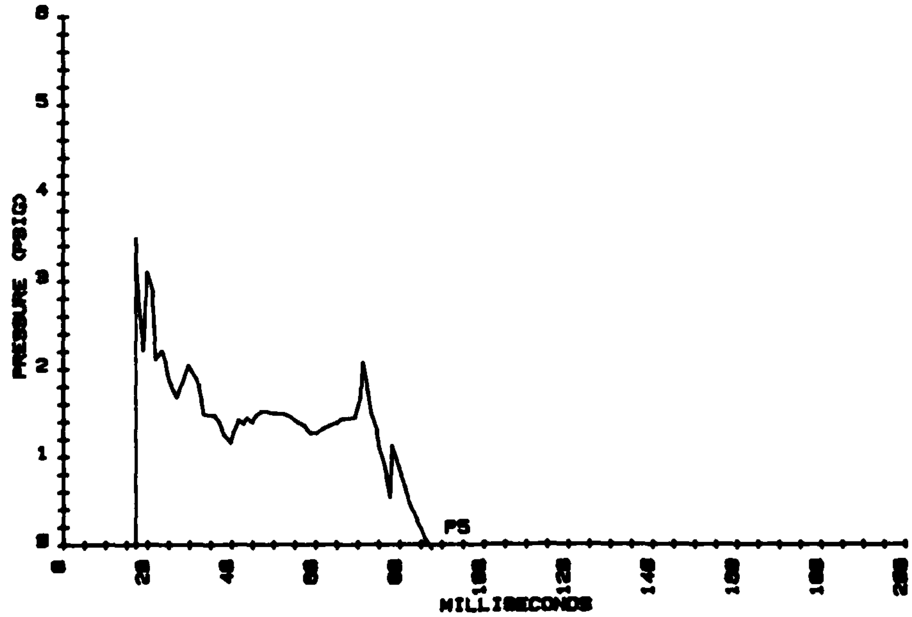


FIGURE D-4 PRESSURE PULSES (SIDE-ON) MEASURED AT SHOCKTUBE WALL (P3) AND AT MIDSTREAM (P5)

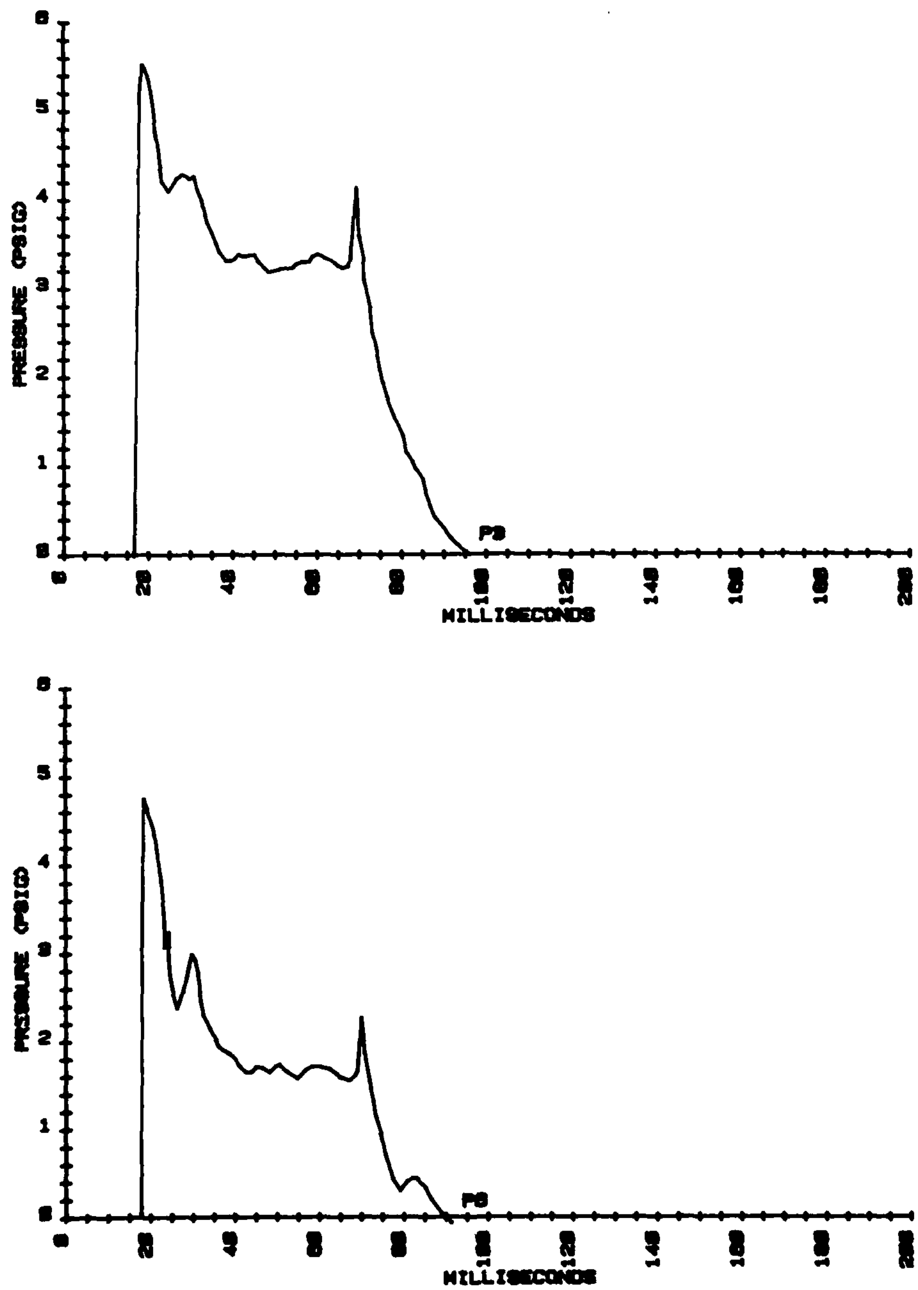


FIGURE D-5 PRESSURE PULSES AHEAD OF THE TEST SECTION (P3) AND ON TEST STAND (P6)

In the majority of the tests conducted so far, the relatively low overpressures (1-10 psi) and the short positive-phase durations used made the cold driver effect unimportant, because the cold gas would arrive at or near the end of the positive-phase duration (overpressures > 5 psi) or after positive phase ended (overpressures < 5 psi). Table D-1 illustrates the timing of the shock and contact surface arrival, for shocks of 2, 5, and 8 psi peak overpressure (calculations courtesy Thomas C. Goodale). It can be seen that only for overpressures > 8 psi can the cold driver gas (contact surface) arrive earlier than ~ 55 ms, which is the end of the pressure plateau, start of rapid pressure decay, and termination of the (positive) pressure pulse (see for example, Figs. D-4, D-5). In tests No. 76-78 and 80, 81, which had high overpressures (8.7-9.8 psi), film records show indications of cold gas arrival at 50-56 ms (50 ms for overpressure over 9 psi), in good agreement with Table D-1.

Another reason for the relatively limited importance of the cold-driver problem in present tests is that for low overpressures the temperature decrease in the "cold" gas is relatively small (compared with flame temperatures). At the initial driver pressure of 29 psig shown in Fig. D-6, the initial gas temperature was 11.5°C; after the pressure drops in the driver to 10.5 psig, the temperature is estimated to drop to -30°C (if isentropic expansion takes place) and the temperature of the driver gas when driver pressure drops to zero gage pressure (at 86 ms) is approximately -60°C. The shuck mean overpressure measured for test 76 (Fig. D-6) was 9.4 psi.

Table D-1

SHOCK AND CONTACT SURFACE ARRIVAL TIMES

Shock overpressure (psi)	2	5	8
Time from shock initiation to shock arrival at test section (ms)	24.9	23.2	21.8
Time from shock initiation to contact surface arrival at test section (ms)	287	123	82.1
Time from shock arrival to contact surface arrival (ms)	262	100	60.3

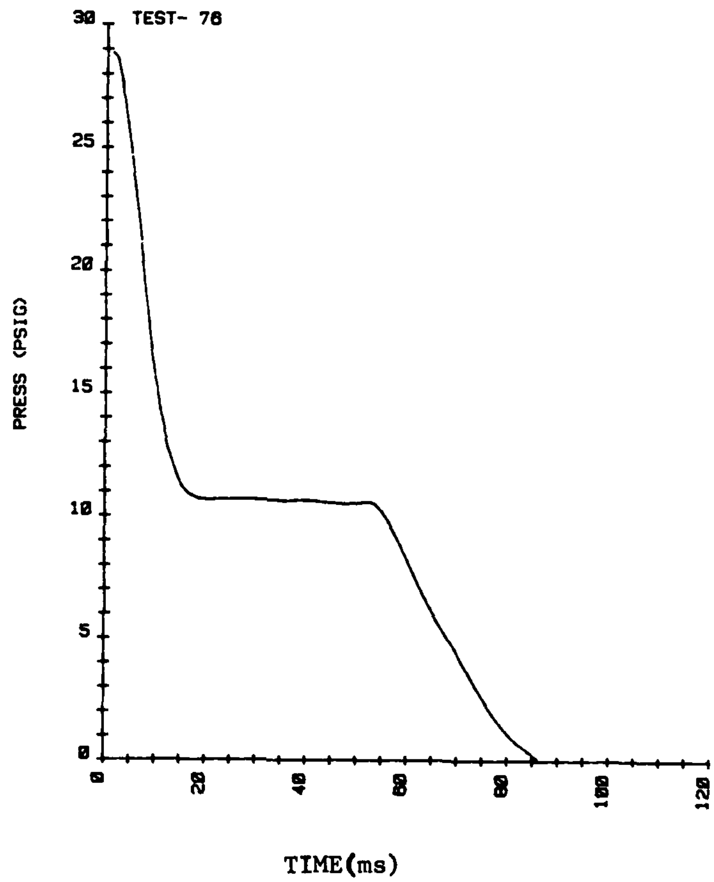


FIGURE D-6 TYPICAL DRIVER-GAS PRESSURE HISTORY FOR SHORT DURATION PRESSURE PULSES (9.4 psi SHOCK)

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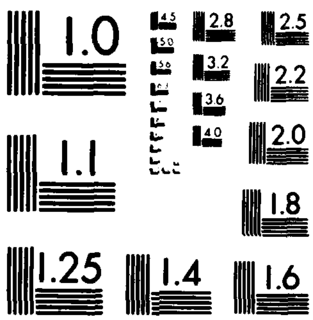

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Experiments on extinction of fires by airblast were continued in the shocktube facility dedicated to blast/fire interactions studies, and the facility was further improved toward a full, thermal/blast simulation capability, which will include a thermal radiation source.

The experimental efforts were aimed toward improving our understanding of the physical mechanisms and scaling rules of blast extinguishment of fires through (1) tests with various common liquid (class B) fuels of different physicochemical properties and burning behavior and (2) tests with wood cribs of various element (stick) thicknesses and consequently varying burning behavior and time scales. Limited shocktube tests were also conducted in preparation for the MILL RACE event featuring blast extinction of fires on cellulosic debris.

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EXPERIMENTAL EXTINGUISHMENT OF FIRES BY BLAST: by Jana Backovsky, Stanley Martin, and Robert McKee. SRI Project PYU 3341, 97 pages plus 6 detachable pages. Contract No. EMW-C-0559, FEMA Work Unit No. 2564 A, Unclassified (May 1982).

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The experimental efforts were aimed toward improving our understanding of the physical mechanisms and scaling rules of blast extinguishment of fires through (1) tests with various common liquid (class B) fuels of different physicochemical properties and burning behavior and (2) tests with wood cribs of various element (stick) thicknesses and consequently varying burning behavior and time scales. Limited shocktube tests were also conducted in preparation for the MILL RACE event featuring blast extinction of fires on cellulosic debris.

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